Geopotential Research Mission (GRM)

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KEYNOTE ADDRESS

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NASA Office of Space Science and Applications

It is my pleasure to be with you today at the GRM Science Conference. This conference is an important part of the process of developing new flight missions. We in NASA management rely on you, and conferences such as this one, to hone to a fine edge the scientific rationale for new missions.

I know that the primary interests of most of you are geodesy and geophysics as they relate to satellite gravimetry. My early association with the space program was with Project ANNA, one of the first efforts to use space for geodesy and geophysics. You and your colleagues have come a long way since ANNA. As Chairman of the Interagency Board on Geodynamics, I can assure you that NASA and the other federal agencies have a continuing interest in helping to push back the frontiers of knowledge in these areas.

Today, I would like to use this opportunity to address the interrelationship between the various disciplines within the earth sciences. I firmly believe that if we are to make progress in understanding our planet and its environment, we must deal seriously with the interaction between the atmosphere, the ocean, the land, and near-space. We must develop a well-thought out research program which focuses on these interactions and seeks to identify long-term trends. Working with your colleagues, and the other agencies, we have started this process through the Earth System Science Committee under Francis Bretherton of NCAR. By the middle of next year, this committee is to produce a plan for an integrated Earth Science Program extending into the next decade.

When we look at the earth as a system, individual processes take on increased significance: weather and climate are powerfully influenced by the transport of water between the atmosphere and the oceans; the redistribution of mass in the atmosphere and atmospheric winds change the earth's rotational rate and its polar motion; the efflux of gasses and dust from volcanoes influences weather and climate and the distribution of aerosols in the atmosphere; the circulation of the oceans through the earth's crust and the flow of sediments from the land introduces mineral salts into the oceans. Recently work by scientists in your own area have shown that fluctuations in the earth's magnetic field, in the rotation rate of the earth, and in the mean temperature of the earth's surface may be related.

The implications of these and many other interactions are clear. In addition to the great scientific interest in understanding

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the dynamic processes that take place in the solid earth and its tenuous gaseous and fluid envelopes, the prospect of attaining or improving the prediction of weather, climate, and natural hazards depends upon how well we integrate and synthesize research in all the disciplines of the earth sciences, and how effectively we make use of the vantage point of space in these efforts.

In all of this, there is a need for long-term observation. The measurements are difficult to carry out, and frequently the effects we are interested in are masked by noise. In the case of the oceans, the atmosphere, the magnetic field and the solar-terrestrial relationships, the very nature of the phenomena changes with time, so that scattered measurements made at one epoch usually cast little light on the underlying phenomena of interest. In studying tectonics of the solid earth, fortunately (or unfortunately depending on how you look at it) the earth is essentially unchanging on the time scale of human lifetimes.

If we are to discern trends, to build models of dynamic processes, and to verify these models of the ever-changing ocean, the atmosphere, and solar influences, it is necessary that the measurements be well-integrated and global in scope. That they be synoptic over the whole earth, and that they continue over a period of time with respect to the trends we wish to observe. This is the basic concept that we are applying to all of our programs dealing with earth science.

To meet the need for interdisciplinary research, NASA has proposed a new international research program called "global habitability." This program has as its objectives the study of changes in weather and climate, the composition of the oceans and atmosphere, and the cycles of energy and mass through the linked earth - ocean - atmospheric system that affect all of us. It is a program, which I believe, makes excellent use of the opportunity that space offers for multidisciplinary, global, synoptic measurements aimed at the solution of important problems.

Although many of its separate components had been underway or planned, the global habitability program brings them together in what has been called, "A Mission to the Planet Earth." The earth radiation budget experiment which was put in orbit earlier this month by the space shuttle, the radar and earth observation experiments which were performed on this same shuttle flight, the upper atmosphere research satellite, and the ocean topography experiment (or TOPEX) are examples of the flight missions that will contribute directly to the objectives of global habitability. In formulating the global habitability program, we considered changes that affect our planet as a whole, and changes that take place on the order of human lifetimes. Here, the solid earth is involved in one more important way; in that, the entire record of past changes in climate is preserved in the geologic record.

Global habitability is also part of a more extensive and expansive international effort being studied by our National Academy of Sciences. The International Geosphere and Biosphere Program, the IGBP, has been the subject of several Academy workshops and studies and is planned to be submitted to International Council of Scientific Unions (ICSU) next year for their endorsement.

The future of solid-earth geophysics and geodesy in NASA, appears bright. The NASA Geodynamics Program, with its close ties and excellent cooperation with other federal agencies and scientific organizations in many countries, is strong scientifically and reasonably well supported financially. We are trying to increase this support, some each year.

We are putting a great deal of emphasis on what we call "land processes" - primarily hydrology and geology - through remote sensing from space. You are all aware of what LANDSAT did for large-scale geological mapping - the images from this satellite have made major contributions to understanding regional geology, especially in remote parts of the world. A carefully planned remote sensing program is being undertaken, with the shuttle imaging radar, the large format camera, and the thematic mapper on LANDSAT 5 expected to make further contributions to geology.

As for the GRM, I can promise you that it will receive very serious consideration in my office. It is now a new start candidate in fiscal year 1988. It is an excellent mission - from a scientific standpoint, from the point of view of practical use of the data, and from the standpoint of feasibility and technological readiness. The introduction of seismic tomography, which will provide a basis for interpretation of the gravity field in terms of vertical and horizontal heterogeneities within the earth has provided a new impetus for GRM. With GRM, questions of the nature of convection in the earth's mantle will be elucidated, as well as tectonic processes taking place in the crust of the earth.

Additional information will be gained on the earth's magnetic field and the high resolution gravity and magnetic field data will make important contributions to geology.

The GRM geoid is required to make full interpretation of the data from TOPEX. Recently a report of the Board of the Joint Oceanographic Institutions (JOI) identified GRM as a high priority mission for oceanography. The improvement GRM will make in our knowledge of the gravity field - over an order of magnitude in accuracy - will result in significant improvements in determining the TOPEX orbit and in tracking other satellites.

I am well aware that the Space Science Board's Committee on Earth Science gave GRM its highest priority recommendation, and I am sure that your efforts will continue to keep GRM in a prominent place as NASA's future plans evolve.

I am looking forward to the report of the Earth Systems Study Committee. Many of you will be participating in the ESSC Solid-Earth Geophysics Working Group, which will be contributing to this report. I am confident that the importance of GRM to the earth sciences will also be evident in the final recommendations of these bodies.

I am proud of NASA's past record of accomplishments in earth sciences. We are planning a bold and imaginative technological research program for the future including global habitability and the geodynamics program. With your help, we will carry this important work forward. I wish you a successful conference.

Thanks.

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I. CONFERENCE SUMMARY

Co-Chairmen:
W.M. Kaula
C.G.A. Harrison

The GRM Science Conference was held October 29-31, 1984 at the University of Maryland, under the sponsorship of NASA, NOAA, DMA, USGS, NSF and NAS. The title of the Conference is derived from the Geopotential Research Mission (GRM), a satellite system proposed to determine variations in the gravitational and magnetic fields to a resolution of about 100 kilometers.

The purpose of the Conference was to review knowledge and interpretations of the potential fields on scales of 100 kilometers and greater, and thus to clarify the needs for better data in this range of wavelengths. In addition, the potential contribution of these data to the determination, by satellite altimetry, of a more accurate geoidal reference was discussed.

The organization of the Conference was: Lithosphere (continental, 7 papers; oceanic, 7 papers; general, 4 papers), mantle convection (10 papers), oceanic circulation (3 papers), and magnetics (12 papers).

Perhaps the most important message of the Conference is that, while there indubitably is a lithosphere much stiffer than the interior, the distinction of 'lithospheric' from 'mantle convective' is definitely not 'passive' versus 'dynamic', a point most strongly emphasized by D.P. McKenzie. This was demonstrated most impressively by K. Lambeck, who showed that a 100 kilometer, 100 milligal gravity anomaly pattern in a central Australian region quiescent for a billion years requires a compression impossible to sustain with simple flexural rigidity and isotasy. More obviously dynamical are the Alps, discussed by H.G. Kahle. The Alps are characterized by zero Bouguer anomaly over the highlands, flanked by -160 mgal anomalies in the Rheingraben and the Po Valley. Subtracting a seismically determined crust leaves a feature of +100 mgal amplitude and 500 km wavelength, suggestive of an upper mantle density anomaly such as a remnant of subducted material. An interesting paper by Humphries & Hager explained seismic and gravity patterns in the transverse ranges of southern California by small scale convection within the uppermost 200 kilometers. Temperature variations of 300 deg. C and shear tractions of about 100 bars are inferred. M.K. McNutt emphasized that while there is a lot of information about continental dynamics in a 100-km resolution field, such data are lacking for many of the most interesting areas, such as the Asian portion of the Alpide belt.

Tectonophysical insight into the oceanic lithosphere has benefited greatly from the radar altimetry of GEOS-3 and SEASAT. As reviewed by A.B. Watts, understanding has greatly advanced concerning: flexural behaviour as a function of age; the nature of oceanic isostasy; the responses of the lithosphere to hot spots; support of sea mounts; and the thermal and mechanical properties of fracture zones. In general, oceanic lithosphere response to loading is explicable as a function of both age of the lithosphere and age of the load. Generally, the lithosphere becomes stiffer with age, thus sustaining greater gravity anomalies. But the "age" can be reset by a hotspot. Interesting modeling presentations were by D.T. Sandwell and C. Liu on the influence of sedimentation of the gravity signal of basement topography, and by P. Olson on lithospheric swells resulting from mantle plumes. On the critical problem of subduction zone dynamics, a review by D.C. McAdoo concluded that the generally believed effect of non-linear rheology cannot be separated from variations in Newtonian viscosity with present data.

Mantle convective studies have been advanced greatly by B. Hager and colleagues at Caltech, who have shown that much of the low degree variation in the gravity field can be accounted for by lower mantle density variations proportionate to seismic velocity variations, supplemented by signals arising from subducted lithosphere and post-glacial rebound. These findings still leave uncertain the question of greatest contemporary concern: the rate of material interchange between upper and lower mantles. Hager asserts the data indicate that there is a thermal coupling, rather than mechanical: i.e., upflows over upflows, which is plausible for a regime whose Rayleigh number is 10,000 times critical. But this signal does not require that subducted slabs plunge beyond the 670 kilometer discontinuity, or that hot plumes ascend through this possible barrier. Related to this matter is the problem of the spectrum of mantle convection. Probably all (not many) who have articulated opinions on the matter believe it to be broad; the question is more whether this spectrum has peaks. D.P. McKenzie proposes there should be three: the longest corresponding to the 2900-km depth of the mantle; the intermediate, to the 670-km discontinuity; and the shortest, to the asthenosphere. Again, this is seeing through a lithosphere darkly. The most striking evidence is from B. Parsons, who, by bandpassing wavelengths between 40 and 500 km from SEASAT altimetry, obtains a lineated pattern of 300 km undulations aligned with the plate motion in Pacific Ocean areas 5-65 My old. The pattern is thus suggestive of instabilities in a low viscosity layer about 100 km thick. However, theory requires a viscosity three orders of magnitude lower than post-glacial in order for an instability to develop within 5 My.

Considerable uncertainty remains as to mantle rheology. The studies of seismic velocity anomalies and gravity by B. Hager obtain a best fit for a lower mantle viscosity 30 times as great as the upper mantle viscosity, taking the boundary to be at 670 km depth. W.R. Peltier also continues to obtain a significant increase in viscosity with depth from post-glacial phenomena, which includes the non-tidal acceleration in rotation. A modelling by R.J. O'Connell obtains two high a heat flow with Hager's viscosity ratio if the coefficient of thermal expansion is 3×10^{-5} throughout the mantle. A study by Yuen & Fleitout shows that temperature and pressure dependence of viscosity result in enhanced instabilities of the flow, leading to smaller geoid variations for a given total heat delivery and mean viscosity: in effect, the flow is more efficient.

J.G. Marsh and collaborators presented a new global mean sea surface computation based on Seasat and GEOS-3 data. Radial orbit error is removed by a multi-stage adjustment utilizing crossover comparisons, so that the final errors in the sea surface are at the decimeter level. B.D. Tapley and G.W. Rosborough discussed orbit accuracies needed for crustal dynamic and satellite altimetry missions, and concluded an order of magnitude increase in accuracy of the geoid is needed for TOPEX. R. Stewart and J. Apel gave separate discussions of the expected contributions of TOPEX and GRM to ocean dynamics. Apel emphasized that GRM is needed for better than 10-centimeter accuracy in determining the time-varying, as well as constant, part of the dynamic height.

Several presentations were made of the interpretation of magnetic anomalies over selected geological features. Ruder and Alexander discussed the interpretation of a total field anomaly (the Kentucky high and the Georgia low) which produce the largest horizontal gradient of total field over the continental United States. They used other geophysical information to constrain their model, and came to the conclusion that the Georgia low is caused by a large body of low susceptibility material throughout the entire lower crust. Small anomalies in vertical magnetic field produced by African hot spots were interpreted by Phillips and Brown to be due to a thinning of the magnetized layer produced by elevated temperatures beneath some of the volcanic zones. Variations in the thickness of the magnetized layer, or variations in the susceptibilty or magnetization of a magnetized layer of uniform thickness are the two major ways of producing long wavelength anomalies. Oceanic magnetic anomalies of long wavelength were discussed by LaBrecque et al., and Frey. It is probable that both induced and remanent magnetization are important in the generation of long wavelength anomalies over ocean basins.

Magnetic anomalies over larger areas of the Earth were discussed by Arkani-Hamed and Strangway, and by Von Frese and Hinze. Arkani-Hamed and Strangway used a method of obtaining an equivalent source magnetization model from spherical harmonics of the magnetic potential approximating a crust of varying vertically integrated susceptibility. This has enabled them to categorize various types of crust according to the magnetic susceptibility values seen. Young oceanic crust shows very low values of susceptibilty, whereas many circum-Pacific subduction zones are marked by positive susceptibility values. Harrison also used a method of inverting spherical harmonics of potential in a simpler way to obtain magnetization variations over the surface of the Earth and found that there was almost no latitudinal variation, and little difference between the strengths of continental and oceanic sources. He suggested that some of the intermediate wavelength signal may originate within the core of the Earth.

A major problem in the interpretation of crustal magnetic anomalies is our lack of understanding of the magnetic properties of the lower crust, which, to complicate matters, is in a state of elevated temperature. Magnetic properties can vary by orders of magnitude for rocks of the same type. Many of the models of individual crustal sources presented at the conference used magnetizations or susceptibilities considerably larger than would be suggested by our current knowledge of the magnetic properties of crustal rocks. Wasilewski discussed some of the problems in determining the magnetic properties of lower crustal rocks and urged others to become involved in this field. Of especial difficulty is that in order to collect rocks from the lower crust, a considerable amount of tectonic activity has to occur to emplace these rocks at the Earth's surface, and subtle effects during tectonism can cause the magnetic properties to change greatly. So it is often not certain that the magnetic properties measured in the laboratory are those pertaining to the rock in its original position. This is true both for continental rocks, and for oceanic rocks obducted onto the continent.

Both Langel and Cain discussed separation of core from crustal fields. The work of Meyer et al. was cited as showing that a significant contribution to the Earth's field could be made by crustal sources, even at very low degrees of harmonic. Cain indicated that spurious secular variation terms could be introduced into the analysis of satellite data by the change in season during the mission, and by the decreasing altitude of the satellite during its life-time. This latter problem will of course be avoided by GRM.

Measurements of the Earth's field are subject to "contamination" by short wavelength fields from the crust at degrees above about eleven in spherical harmonic models. Because they are amplified in the process when projected to the Core-Mantle Boundary (CMB), these short wavelength fields distort our picture of the field. In order to eliminate this effect, Shure et al. and Bloxham and Gubbins have derived models which are optimally smoothed at the CMB. A selected set of Magsat data were analyzed by both groups and contours of the radial field at the CMB were derived. These show more detail than previously derived smoothed models. Bloxham and Gubbins have also derived error bounds on the field at the CMB, although some dispute their validity. They also computed smoothed models at 1970 and 1960 which showed nearly identical patterns to the field at 1980. These models are consistent with the frozen-flux hypothesis for the core, and exhibit features which could be interpreted as MHD waves in the core.

It is not possible to compute unique fluid velocities at the CMB from magnetic field data alone unless some additional simplifying assumption is made. Voorhies has performed calculations under the assumption of steady fluid flow at the CMB. This assumption can then be tested by comparing the self-consistently computed magnetic secular variation with the measured secular variation. Steady flows which are purely toroidal do not result in fluid flows consistent with secular variation models. Flows with combined toroidal and poloidal components fit the known secular variation at the CMB to within 30% for intervals of up to 20 years. Since the accuracy of the known secular variation at the CMB is estimated to be worse than 17% (about 27% for 1960-1980), these results provide evidence for weak vertical flows near the CMB. GRM measurements combined with the existing Magsat measurements may have the capability of providing large scale secular variation accurate to about 13% at the CMB, which should be sufficient to make more definitive studies of vertical flow.

Near-earth models of the geomagnetic field, $\vec{B}$, are formulated by assuming that $\vec{B} = -\nabla V$, where V is a scalar potential. Because satellite measurements are made in and above the ionosphere, and in particular in the region where field aligned currents are known to flow, these assumptions are only approximations. G. Backus addressed the problem of modeling fields in the presence of currents, with particular emphasis on dealing with field aligned currents when the measurements are confined to a thin shell.

Benton focused on exploiting the similarity of the inviscid radial vorticity equation to the frozen-flux induction equation at the top of earth's core. Of particular interest is the uniform density case in which radial Coriolis torques dominate radial Lorentz torques. In this case, the contour of zero absolute radial vorticity, which lies very near the geographic equator, always consists of the same fluid parcels - just as do contours of zero radial magnetic field. Both the absolute radial magnetic flux and the absolute radial vorticity linking both null-flux and 'null-vortex' contours must then be conserved. In addition to several powerful constraints on core motions, this fact provides a particularly tractable constraint on the geomagnetic secular variation. By extending the useful data span by 50%, the GRM would permit testing this plausible dynamical hypothesis.

II. Continental Lithosphere

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IMPACT OF GRM: NEW EVIDENCE FROM THE SOVIET UNION

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Gravity information recently released by the Soviet Union allows us to make some quantitative assessment of how the GRM mission might affect our ability to use global gravity data for continental tectonic interpretation. The information released is of the form of isostatic response spectra for eight individual tectonic units in the USSR calculated by M.G. Kogan of the Institute of Physics of the Earth in Moscow. The regions examined include the Carpathians, Caucasus, Urals, Pamirs, Tien-Shan, Altai, Chersky Ridge, and East Siberian Platform. The $1^o \times 1^o$ gravity data used to calculate the admittances remain classified by the Soviet government. To date, the admittances have been used in two different sorts of tectonic studies of mountain belts in the USSR.

In the first study, McNutt and Kogan (1985) attempted to directly interpret the isostatic responses in terms of plate models of compensation for mountainous terrain. Using geologic information concerning time of the orogeny, lithospheric plates involved, and polarity of subduction in collision zones, they convert the best-fitting flexural rigidity to an elastic plate thickness for the lithospheric plate inferred to underlie the mountains. Combining the new results from the Soviet Union with rigidity estimates for other continental plates, McNutt and Kogan (1985) confirm a trend noted by Karner and Watts (1983) for older plates to yield larger values of elastic plate thickness. This observation is consistent with thermal control for lithospheric strength. Furthermore, McNutt and Kogan (1985) also found that even very old, archean plates in some cases display low elastic thickness values, particularly when the curvature of the fold/thrust belt is high. If, as in the oceanic analogue, highly arcuate belts correlate with steeply dipping slabs, this observation implies that even old continental lithosphere appears elastically thin when sharply bent. The reduction in elastic thickness with increase in plate curvature could help constrain models of finite yield strength for continental crust and mantle. However, McNutt and Kogan's (1985) conclusions remain extremely tentative since they are based on a few noisy spectra from gravity and topography data sets with low coherence. Forward modeling of actual gravity and topography data is vitally needed.

The second study using the isostatic admittance functions is an attempt to directly model gravity and topography data for a few select regions in the Soviet Union. Artemjev has published several grey-toned isostatic anomaly maps for several areas of the USSR (e.g.

Artemjev and Dosymov, 1974; Artemjev and Balavadze, 1973) assuming Airy compensation. Although his maps have no coordinates and no scale, thus appearing useless for quantitative analysis, because the compensation as indicated by the admittances is more regional than the assumed Airy mechanism, Artemjev's isostatic residuals are strongly correlated with topography. Knowing the value of the expected correlation between topography and gravity from the admittances, we can calibrate Artemjev's map in mountainous areas, and convert the maps back to Bouguer gravity. This procedure has been applied to the Caucasus and southern Urals. We are presently in the process of modeling the gravity data.

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DYNAMICS AND STRUCTURE OF THE ALPINE FOLD BELT

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Several recent measuring campaigns have made it possible to discuss the structure and present-day dynamics of the Alps in terms of geodesy and gravimetry. Recent uplift rates obtained from repeated precise levelings and isostatic gravity anomalies show a strong correlation along the central Alpine chain, especially in Canton Graubunden, East Switzerland. It is tempting to assume that the uplift there is partly controlled by isostatic rebound effects. Field observations indicate that these phenomena are still active in the Alps. It is therefore planned to study the uplift processes by applying a number of geodetic and gravimetric measuring techniques, such as the determination of non-periodic secular variations of gravity, of the deflections of the vertical and tilt changes monitored by hydrostatic levelings.

Future projects in the field of gravimetry and geodynamics in Switzerland are focused on international projects, such as the International Lithosphere Project (ILP), the European Geo-Traverse (EGT) and NASA's Crustal Dynamics Project. Of particular importance are intermediate wavelength components of the gravity field which are indicators of deep seated mass anomalies most likely being associated with lithospheric subduction during continent-continent collision.

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WHY DO WE NEED DETAILED GRAVITY OVER CONTINENTS: SOME AUSTRALIAN EXAMPLES

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Apart from terrain elevations the only geophysical quantities that are generally available over a continent are gravity and components of the magnetic field. Hence direct inferences on crustal structure are difficult to make and strongly dependent on mechanical assumptions made. For example assumptions concerning the isostatic state. The data for Australia represents one of the best continental scale gravity surveys and provides some useful examples of what conclusions can be drawn from such data. The gravity anomalies are generally bland over the continent and this is in keeping with the notion that stress relaxation and erosion and rebound have been instrumental in reducing non-hydrostatic stresses. Notable exceptions, however, occur. In central Australia very large gravity anomalies occur and the region is out of isostatic equilibrium despite the fact that tectonic activity ceased 300 ma ago. Here the isostatic response functions points to there being substantial horizontal compression in the crust. Similar conclusions are drawn for the large anomalies in western Australia. The tectonic implications of these anomalies will be examined. In eastern Australia the gravity anomalies are explained in terms of a model of erosion of the highlands and concomitant regional isostatic rebound.

These examples illustrate that gravity over continents can be used as a reconnaissance tool to determine the general stress-state of the interiors of continents, and to permit preliminary evaluations to be made of the principle tectonic features. Detailed gravity measurements over the less-well surveyed continents would determine whether some of the Australian examples are really exceptional or whether they are typical of stable tectonic environments.

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A MAJOR CRUSTAL FEATURE IN THE SOUTHEASTERN UNITED STATES INFERRED FROM THE MAGSAT EQUIVALENT SOURCE ANOMALY FIELD

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The Magsat equivalent-source anomaly field evaluated at 325 km altitude (Mayhew, et al., 1984) depicts a prominent anomaly centered over southeast Georgia. This -10 nT, 400 km feature is adjacent to the high-amplitude positive Kentucky anomaly. Together, the two anomalies share a 30 nT, 650 km gradient, the steepest in the conterminous United States equivalent source field. The Georgia negative anomaly extends northeast along strike of the Inner Piedmont geologic province, as far north as Virginia. To the southeast, it grades into an offshore negative anomaly which lies between the Blake Plateau and the Bahamas. In an attempt to overcome the satellite resolution constraint in studying this anomaly, we include conventional geophysical data in the analysis: Bouguer gravity, seismic reflection and refraction, aeromagnetic, and in-situ stress-strain measurements; through this integrated geophysical approach, we can infer more specifically the nature and extent of the crustal and/or lithospheric source of the Georgia Magsat anomaly. Physical properties (composition, susceptability contrast, crustal thickness) as well as tectonic evolution of the area are all important in the interpretation.

In assessing the nature of regional magnetic crust, we address four problems: What are the structural magnetic units of the southern Appalachians? What is the magnetic expression of the edge of the ancient craton? Does the magnetic crust reflect the seismic crust in this zone of low (< 1 HFU) heat flow? How useful is the equivalent source anomaly field in highlighting this anomalous crustal zone? Using this data set, what can we learn about crustal magnetization?

The study area has experienced both extensional and compressional tectonics. Precambrian rifting and normal faulting gave way to Paleozoic compression and overthrusting. Accretion of terranes and three successive orogenic episodes occurred during this era. The Appalachian decollement and other indications of thin-skinned tectonics are superimposed Paleozoic features. A dramatic change to an extensional stress regime led to Mesozoic rifting and the successful opening of the Atlantic Ocean. The modern stress field is characterized by northeast maximum horizontal compressive stress (Zoback and Zoback, 1980, 1984), probably generated by ridge-push from spreading along the Mid-Atlantic ridge.

The Appalachian orogen, as well as the Georgia anomaly, is comprised of allochthonous terranes (Hatcher and Williams, 1982). Identified terranes whose dimensions are on the order of Magsat's spatial resolution include the Piedmont, Avalon, Brunswick, and Tallahassee. The Piedmont terrane is characterized by linear aeromagnetic anomalies and near-surface mafic and ultramafic rocks. Precambrian sedimentary and volcanic (calc-alkaline to tholeiitic) rocks are found in the Avalon. These are expressed as high-frequency, short-wavelength aeromagnetic anomalies. The Brunswick and Tallahassee terranes are obscured by Coastal Plain sediments. Unlike the Avalon and Tallahassee terraines, the Brunswick contains broad-wavelength aeromagnetic signatures.

Within these individual terranes, prominent geophysical features outline large-scale crustal blocks. Although it is best experienced as a magnetic anomaly, the northeast-trending New York-Alabama Lineament (King and Zietz, 1978), it also correlates with Bouguer gravity. The feature may repreent a Paleozoic or older subduction zone or a major strike-slop basement fault. To the southeast lies the Appalachian gravity low and northeast-trending anomalies. North-trending anomalies are found northwest of the New York-Alabama lineament. The Clingman lineament (Nelson and Zietz, 1983), another aeromagnetic linear feature within the study area is located 60 km to the east; it likely represents a basement structural discontinuity, as well. The region of eastern Tennessee which lies between these two linear features has the highest seismicity of the southern Appalachians (Johnson, et al., 1984).

The large amplitude, paired negative and positive Bouguer anomaly, the Appalachian gravity gradient, transects the Inner Piedmont. Its northeast trend through the study area may outline the edge of the ancient North American craton. The gradient has been modeled as a suture by Hutchinson, et al. (1983) and its flexural properties have been investigated by Karner and Watts (1983).

Although seismic reflection profiling represent the clearest geophysical crustal imaging technique, COCORP results in the study area are ambiguous. According to Cook et al. (1979), the decollement is resolved throughout the region. However, reprocessed sections interpreted by Iverson and Smithson (1983) indicate that the detachment root zone is located in the Piedmont, and no midcrustal reflectors are identified east of this province. The nature of the detachment remains an unsolved question, central to the tectonic interpretation of the study area.

Our preliminary results indicate that the Georgia magnetic anomaly is caused by a large volume of low susceptibility material distributed through the entire lower crust beneath the decollement. The argument for the alternative of a thinned magnetic crust is eliminated upon examination of the low heat flow (no elevated Curie isotherm) and crustal thickness estimates from seismic data. Forward modeling results of Ruder and Alexander (1984) show a four-body model with vertical and lateral susceptibility discontinuities can reproduce the general features of the anomaly field. By incorporating the geophysical evidence discussed above, crustal magnetization blocks are presently being further delineated by aeromagnetic lineaments, the gravity gradient and seismic profiling results. It appears that major magnetization units may be correlated with the allochthonous terranes present in the study area, and hence with the regional tectonic fabric.

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GEOPHYSICAL INTERPRETATION OF THE MAGNETIC ANOMALIES OF THE EARTH DERIVED FROM MAGSAT DATA

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A global scalar magnetic anomaly map does not show a direct correlation between magnetic anomalies and their causative sources. A positive scalar magnetic anomaly near a geomagnetic pole can be associated with a positively induced magnetic body, whereas such a body creates a negative anomaly near the geomagnetic equator. A magnetic anomaly of an induced magnetic body appears approximately over the body at high and at low geomagnetic latitudes, while it is displaced toward the equator at mid-latitudes, creating a lobe toward the respective pole with opposite sign. Furthermore, a magnetic body with a given magnetic susceptibility produces a stronger anomaly at higher latitudes than at lower latitudes, since the main geomagnetic field is weaker and almost horizontal at lower latitudes. These ambiguities pose questions about geophysical implications based on the correlation of scalar magnetic anomalies and geological features. They also hamper the comparative interpretation of widely separated anomalies. A method is developed in order to convert scalar magnetic anomalies into a map of the lateral variations of magnetic susceptibility of the lithosphere (susceptibility anomalies). This map can be directly correlated with the causative sources. The method is based on spherical harmonic analysis of lateral variations seen on the scalar magnetic anomaly map and those of the lithospheric magnetic susceptibility. Their harmonic coefficients are related through the fundamental causality relationship governing a magnetized body and its associated scalar magnetic anomaly. The main features of the resulting magnetic susceptibility anomalies are as follows.

Young oceans have relatively low magnetic susceptibility anomalies, implying that the oceanic lithosphere is relatively more uniform than the lithosphere beneath the continents. Oceanic regions younger than about 80 Ma (except the South Indian Ocean) have almost no magnetic signature, suggesting that under the young lithosphere, there is only a very small volume of material below the Curie point. Many Circum-Pacific subduction zones have positive susceptibility anomalies. This can be related to the downward displacement of the Curie isotherm by the cold subducting plates.

Continental and old oceanic lithosphere has relatively more significant susceptibility anomalies than the young oceanic lithosphere. Anomalies in different continents are quite similar. There is no obvious correlation between susceptibility anomalies and major shields. However, small scale cratons have positive susceptibilty anomalies. Most of the aulacogens associated with the rupture of the Atlantic Ocean, some modern uplifts and recently reactivated old rifts seem to correlate with negative susceptibility anomalies. All these anomalies can be explained by a common model. Major shields are locally demagnetized by hot spots or by intrusion of hot material into rifts so that they are effectively fragmented into several small blocks. The demagnetization effects of a hot asthenospheric intrusion into the lithosphere are studied on the basis of the thermal evolution of different intrusion models. It is concluded that the initial temperature perturbations of the lithosphere caused by a hot asthenospheric intrusion require about 200 Ma to decay to a negligible magnitude, in accordance with the demagnetization model proposed.

SATELLITE MAGNETIC MODELING OF NORTH AFRICAN HOT SPOTS

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One of the primary objectives of the MAGSAT mission was to measure the intensity and direction of magnetization of the Earth's crust [Lange, 1982]. A significant effort has already been directed to the large crustal anomalies first delineated by the POGO mission, but the MAGSAT data are capable of spatial resolution of the crustal field to 250 km wavelength with reliability limits to less than 1 nT in the mean [Sailor et al., 1982]. One of the difficulties of dealing with less than the most robust of the MAGSAT anomalies is that often we have no more than the magnetic fields themselves to constrain geophysical models of the interior, and thus do not have an independent means of assessing the quality of the crustal anomaly data in interpreting the subsurface.

Mayhew [1982b] has used satellite magnetic data to constrain Curie isotherm depths. Using an equivalent layer magnetization model derived from magnetic anomalies measured by the POGO satellites [Mayhew, 1982a], he was able to demonstrate in the Rio Grande Rift a remarkable correlation between heat flow predicted by magnetically-derived Curie isotherm depths and the regionally smoothed measured heat flow values. In the absence of heat flow data, or in the presence of badly scattered observations, alternative manifestations of the thermal structure of the lithosphere might be used to test the utility of satellite magnetic data to determine Curie isotherm depths. In turn, confidence in the Curie depth estimates will establish regional lithospheric thermal structure. We have considered a model of thermal isostasy as an indirect means of determining lithospheric thermal structure (and by implication, heat flow) to test against satellite magnetic data.

We have used the North African volcanic provinces of Ahaggar, Tibesti, and Darfur to provide a means of evaluating the MAGSAT data. On the basis of the hot spot tectonic hypothesis [Burke and Wilson, 1972] that these regions mark concentrated excess heat flow from the mantle, it was possible to construct a simple, testable susceptibility model of the lithosphere to test against the MAGSAT data.

The notion that the elevated basement [Gass et al., 1978] of these hot spot regions is due to thermal isostasy leads to a simple relationship between the lithosphere-asthenosphere boundary depth, D, and mean lithosphere density, mean asthenosphere density, thermally perturbed topographic elevation, h, and the thickness, L, of a reference (non-perturbed) lithosphere [Morgan and Phillips, 1983]. If heat sources in the lithosphere are ignored, then the depth to the Curie isotherm is the product of the ratio of Curie temperature to asthenosphere temperature and the lithosphere depth D. The depth to the Curie isotherm is therefore a direct function of topographic elevation but is dependent on assumed physical properties of the lithosphere. Some help is available from seismic, heat flow and gravity variations [Gass et al., 1978]. The most direct constraint is provided by Crough [1981a,b], who has estimated mean isostatic root depths of 50 and 60 km for Darfur and Ahaggar, respectively. This directly constrains the density dependence of the Curie depth for a given value of L, which may lie between values of 100 and 200 km. Indirect estimates [Fairhead and Reeves, 1977; Gass et al., 1978] of lithospheric thickness suggest a reference value of about 200 km. This value may be only typical of cratonic areas, and a lesser value may be more appropriate as a reference in non-cratonic regions.

For the study undertaken here, the dominant lateral variation in lithospheric susceptibility was taken to be variations in depth to the Curie isotherm, as discussed above. If ferromagnetic mineralization is confined to the crust [Wasilewski et al., 1979], the operative depth is the Moho or the Curie depth, whichever is shallower. For an assumed value of L, the topography of the Curie isotherm surface is obtained from quarter-degree averages of the surface topography in North Central Africa. The magnetic field predicted at the MAGSAT spacecraft altitude is obtained frm these two surfaces by Fourier transform techniques, following Parker [1972] but allowing for spatial variation in the direction of magnetization.

We have generated vertical component maps at MAGSAT orbital altitudes of these lithospheric thermal models. The region of the North African hot spots is magnetically bounded by the Bangui anomaly on the south, the positive anomaly associated with the West African Craton on the west, and the magnetic high associated with the Mediterranean and southern-most Europe on the north. Since we have not modeled these features, our interpretation is confined to those thermal anomaly patterns interior to this magnetic boundary. In this region our model can account for the sign (polarity) and position of the two major anomalies seen on the published vertical component map [Langel et al., 1982]. As predicted by the model, the negative anomaly at approximately 22 deg N, 10 deg E is associated with the Ahaggar hot spot and the positive anomaly centered at approximately 15 deg N, 22 deg E is associated with the Darfur hot spot.

We recognize difficulties with both the model and the data. In the former case it is the simplifying assumptions, the most significant of which may be that all *input* parameters to the model are laterally uniform except for the surface topography. In future modeling efforts we hope to obtain a better regional characterization of the lithosphere by employing satellite-to-satellite tracking (SST) gravity data.

A more serious problem may be the quality of the data itself. The smaller anomalies are close to or less than the *spectral* coherence limit of 700 km wavelength as determined by Sailor et al. [1982]. A Kp cutoff of 2 on the data produces a more spatially coherent map pattern in North Central Africa than a Kp cutoff of 3. The former data set (as derived from "Investigator-B Tapes") is, however, relatively sparse over much of this region, and coherence tests of data taken at different times over the same region are very limited. Further, the sparseness of the data leads to a significant sensitivity of the disposition of the small anomalies and the details of the large anomalies to the type of averaging procedures used on the data set. These considerations affect our ability to use the data to estimate model parameters.

We are continuing to address the data questions and relate the results to the sensitivity of the thermal model parameters. Such results will be useful for future magnetic mapping missions.

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MAGNETIC STRUCTURE OF THE CRUST

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Unique interpretive problems emerge when one tries to model the large scale crustal magnetic anomalies. The full thickness of the magnetic crust by areal dimensions of a craton may be the crustal volume to be modeled, or perhaps the geometric volume of a subduction zone. Embodied in some volumes may be a billion years of earth history with consequent lithologic additions and modifications, all complicated by numerous tectonic events. It is apparent that the non-uniqueness aspect of geophysical interpretation must be constrained by geological insight in order to limit the range of theoretically possible models. However, an additional step is required, namely, an in depth understanding of the relationship between rock magnetization and geological circumstances on a grand scale. Typical block models on this scale are quite deficient and inappropriate.

Emerging views about crustal structure and the distribution of lithologies certainly suggests a complex situation with lateral and vertical variability at all levels in the crust. Volcanic, plutonic, and metamorphic processes together with each of the observed anomalies. Certain important questions become prominent and are being addressed currently.

- Where is the magnetic bottom?
- Is the source a discrete one or are certain parts of the crust cumulatively contributing to the overall magnetization?
- If we localize the anomaly to some recognizable surface expression, then how do we arrive at a geologically realistic model incorporating magnetization contrasts which are realistic?
- In what way are the primary mineralogies altered by metamorphism and what are the resultant magnetic contrasts?
- What are the effects of temperature and pressure on magnetization?

There is no direct way to access the deeper regions of the crust. However, xenoliths brought to the surface in kimberlite and alkalai basalt, tectonically exposed crustal sections, Precambrian amphibolite/granulite metamorphic terrain, the ophiolites, and dredged oceanic rocks from fracture zones do provide access to lower crustal lithologies, though one must be careful in evaluating the magnetic properties.

The classical seismic refraction velocity discontinuity (Figure 1A) locates the Moho. Is this boundary a magnetic boundary? We asked this question (Wasilewski et al., 1979) and (a) surveyed the literature (see for example, Haggerty, 1977) to find overwhelming evidence suggesting that Fe^{2+} and Cr in non-magnetic normal spinels dominated the oxide components in upper mantle rocks, with Fe^{3+} and Ti in magnetic inverse spinels partitioning to the crust, and (b) we measured the magnetic properties of upper mantle xenoliths and found them to be virtually non-magnetic except in cases where decompression melt is obvious. From this evidence it became apparent that the Moho as defined in the classical sense was indeed a magnetic boundary, except where the magnetite isotherm surface resides above the Moho and correspondingly becomes the magnetic bottom. The reason for the choice of the magnetite isotherm (~550°C) became obvious when an extensive study and review of exsolution, oxidation, serpentinization and metamorphism was concluded. Magnetite with minor impurities appears to be the dominant magnetic mineral in the crust.

Reports of detailed seismic reflection studies emphasized the lithologic complexity of the lower crust. The Moho is best defined as a position of the maximum velocity gradient after a gradational lower crustal profile. Laminations may be present at the crust-mantle boundary due to cumulate layering or other causes (see Figure 1B). However, in this modified classical model there does not appear to be any reason to modify the magnetic source conceptualization developed earlier. However, the gradational nature of the lower crustal velocity profiles indicates increasing rock basicity with depth allowing a potential source of increased magnetization.

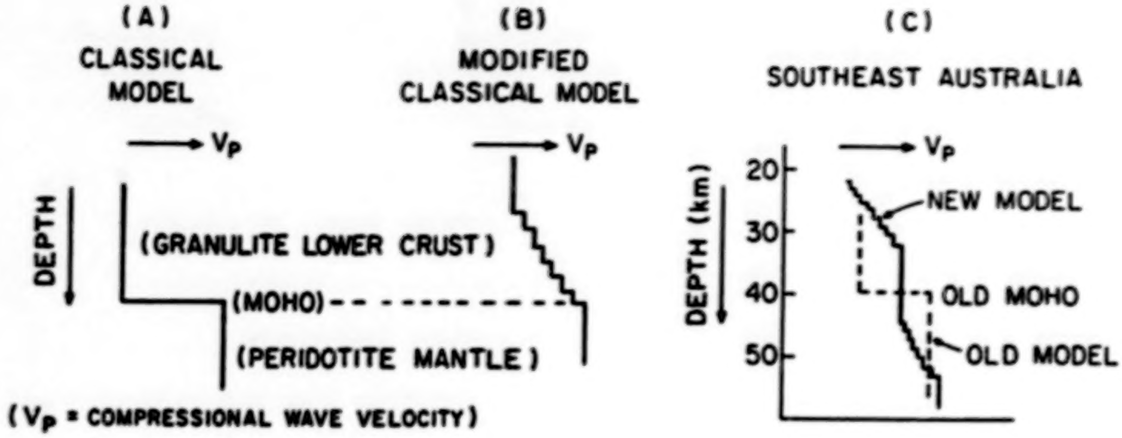
In Figure 1C a specific case (SE Australia) is presented to demonstrate the contrast between the old seismic refraction model and the new model based on more recent detailed studies (Ferguson et al., 1979, Wass and Hollis, 1983, Griffin et al., 1984). The laminated transition zone is attributed to mafic/-ultramafic interlayering associated with extensive underplating. This region has anomalously high heat flow and regardless of the implications of the new model, the region of crust below 20 km is non-magnetic.

Curie points in the the crust are dominantly magnetite, however, in principle any phase from Fe_3O_4 to Fe_2TiO_4 is possible. It turns out, as mentioned earlier, that oxidation and exsolution invariably produce magnetite (~540-575°C) Curie points. In regions of high heat flow, such as rift zones and certain subducting regimes where conditions are anhydrous, reduction prevails and ilmenites and ulvospinel rich titanomagnetite are the dominant oxides. In the study of xenoliths care must be exercised as partial fusion during decompression can result in oxide phase reduction, garnet and other silicate decomposition, thereby producing magnetite, hercynite and even metallic iron (as reported by Haggerty at the Magsat investigators meeting).

Most xenoliths from the lower crust are in the granulite facies. In the crustal cross section considered in some detail by Fountain and Salisbury (1982) the lower crustal material is in the granulite facies and is overlain by amphibolite facies. The significant vertical zonation in the crust from a magnetic viewpoint may be metamorphic zonation. Granulite facies rocks usually contain discrete ilmenite and magnetite, while retrogression to amphibolite facies may produce more or consume magnetite. There is little systematic information about magnetization contrast in progressive or retrograde metamorphism.

Considerable laboratory work is required to understand the origins of magnetization contrasts in the context of crustal evolution, a prerequisite for effective modeling of long wavelength magnetic anomalies. In the context of potential field mapping a correspondence must be established between the origins of density and magnetization contrasts since this capability will refine our interpretive skills. This presentation will review our state of knowledge about:

- The distribution of minerals and Curie points in the crust,
- The location of this magnetic bottom,
- The distribution of lithologies and associated magnetization contrasts,
- The effects of metamorphism on magnetization contrasts, and
- The development and modification of magnetization contrast due to crustal processes such as metamorphism, oxidation, reduction, exsolution and serpentinization.


(A)
CLASSICAL MODEL
(B)
MODIFIED CLASSICAL MODEL
(C)
SOUTHEAST AUSTRALIA
→ Vp
DEPTH
(GRANULITE LOWER CRUST)
(MOHO)
(PERIDOTITE MANTLE)
DEPTH (km)
20
30
40
50
NEW MODEL
OLD MOHO
OLD MODEL
(Vp = COMPRESSIONAL WAVE VELOCITY)

- FeTi OXIDES IN GRANULITE FACIES LOWER CRUST (MAGNETIC)
- CHROMIUM SPINELS AND MAGNESIAN ILMENITES IN MANTLE PERIDOTITES (NON MAGNETIC)
- NORMAL CONTINENTAL LOWER CRUST DOMINATED BY Fe_3O_4 (CURIE POINT 550-580°C)

MOHO IS THE MAGNETIC BOTTOM UNLESS TEMPERATURES ABOVE THE MOHO EXCEED ~550°C; THEN THE ~550°C ISOTHERMAL SURFACE IS THE MAGNETIC BOTTOM

Figure 1 - Simple and more complicated views of the crust-mantle boundary.

III. Oceanic Lithosphere

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GRAVITY, GEOID AND THE OCEANIC LITHOSPHERE

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The Earth's gravitational field has proved one of the principal methods by which to determine the structure of the ocean basins and the continental margins. Early studies led to the development of commonly accepted models for the crustal and upper mantle structure of mid-ocean ridges, seamounts and oceanic islands, island arc-deep sea trench systems, fracture zones, and passive continental margins. These studies provided information on the mass distribution that could cause a gravity or geoid anomaly. However, they provided little information on the geological processes occuring at these features. As a result, the Earth's gravitational field was not one of the principal observations on which the concept of plate tectonics was based. This concept was based instead primarily on observational data from earthquake seismology, marine magnetism, and paleomagnetism.

During the 15 years since the development of plate tectonics there has been considerable progress in studies of the Earth's gravitational field. In acquisition, the development of forced feed-back accelerometers, satellite navigation, and satellite radar altimetry have significantly improved the accuracy and coverage of gravity data over the oceans. In interpretation, gravity and geoid anomalies have been used to determine information on the thermal and mechanical properties of the oceanic lithosphere and the forces that drive plate motions.

In this lecture, we will review the contributions that have been made by studies of the Earth's gravitational field to our understanding of the oceanic lithosphere. Particular emphasis is given to studies of the thermal and mechanical properties of oceanic lithosphere. There are two main reasons for this: a) the thermal and mechanical properties of the lithosphere contribute to most of the energy in the short-wavelength gravity and geoid spectrum, b) the thermal and mechanical properties and their variation with age have important implications for studies of the tectonic setting of bathymetric features on the ocean floor, the evolution of sedimetary basins, the origin of fracture zone topography, bathymetric prediction, the separation of mean ocean currents from satellite radar altimeter data, and mantle convection. Moreover, a number of missions are planned in the future (e.g., TOPEX, GRM, satellite gradiometry) in which the Earth's gravitational field will be measured to a much greater temporal and spatial resolution.

N86-12861

THERMAL COOLING OF THE OCEANIC LITHOSPHERE FROM GEOID HEIGHT DATA

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To study thermal cooling of the oceanic lithosphere another type of geophysical observation has proved recently to be very useful: it is the geoid height derivative with respect to plate age, a quantity computed from the short wavelength geoid step across fracture zones measured by altimeter satellites.

Cooling of the lithosphere causes the geoid height to decrease regularly with increasing plate age with a symmetrical behavior with respect to the ridge crest. This geoid is in turn responsible for the geoid offset observed across fracture zones due to the abrupt change in plate age between the two sides of the fracture zone. The variation in geoid height due to lithospheric cooling is typically of 5-10 m over distances of 1000-2000 km, which is very difficult to isolate from other unrelated long wavelength anomalies. Fortunately, geoid offsets across fracture zones represent a particularly useful constraint: such is the case because fracture zones give rise in the geoid to a characteristic step-like signature, downward from the younger, shallower side to the older, deeper side, with an amplitude ranging from a few tens of centimeters to a few meters over distances of 100-150 km. This signature is easily detectable and presumably little contaminated by medium and large scale features unrelated to cooling. The geoid offset observed across fracture zones divided by the age offset represents the first order derivative with respect to age of the geoid slope due to lithospheric cooling. If the age on the two sides of the fracture zone is known, and observed the (geoid offset over age offset) versus age relation can be established and compared to theoretical relations computed from the cooling models, allowing an estimate of some thermal parameters from fits to the data.

Two categories of simples models have been proposed to describe cooling and contraction of the oceanic lithosphere with age. Both plate model and half-space model, give almost similar results up to ages of 50-70 ma but predict quite distinct behavior of seafloor depth, heat flow and other parameters in old basins. To date, tests of thermal models have been mainly based on heat flow and topography data. However, heat flow is not very sensitive to the form of the thermal model. On the other hand, large areas of the ocean floor are particularly shallow, and as a result topography data may not be very appropriate to discriminate between plate and half-space models, so that no clear concensus on a preferred model as yet exists.

N86-12861

We have analyzed Seasat geoid height data across 15 fracture zones of the South Pacific and Northeast Pacific. We find that geoid data clearly appear incompatible with the half-space cooling model at all plate ages and that for plate ages larger than 30 ma, the data follow reasonably well the behavior predicted by the plate model with a thermal thickness of 95 km. However, at younger plate ages, this conclusion no longer holds: the data could still be interpreted in terms of plate model with a plate thickness of 65 km but do not present the same initial behavior seen in the model curves. These results suggest the existence of two distinct trends: one for seafloor ages less than 30 ma, the other for ages greater than 30 ma. The apparent thermal thinning in the younger portion of the plate might result from a thermal perturbation beneath the plate. From the analysis of geoid data, it appears that the thermal evolution for young lithosphere is more complex than that described by the usual plate model in its simplest version and these observations would offer important constraints on any proposed alternative. Besides, it would be important to know if the behavior observed in the Pacific is specific to that ocean or instead is a worldwide phenomenon. In addition to analyze Seasat data in other oceans, the use of the future GRM data no doubt will help to bring a better understanding of this important problem.

N86-12862

STUDIES OF THE MARINE CRUSTAL MAGNETIZATION AT INTERMEDIATE WAVELENGTHS

J.L. LaBrecque, S.C. Cande and C.A. Raymond

The marine data set can be filtered at intermediatae wavelengths to provide a data set which complements the satellite fields of Magsat, TSS and GRM.

Separation of core and crustal souces is difficult in the $10 \leq N \leq 16$ transition spectrum. The GRM (epoch 1992.0) will return a high resolution data set which will complement the Magsat (epoch 1980.0) and the sea surface data set (epoch 1970.0). The three fields are separated by a decade each, hence the analysis of westward drift components may help to separate the crustal from main field components within the anomaly transition spectrum.

The filtered marine data set provides a high resolution data set which is closer to the source bodies than satellite survey data. However, the GRM and TSS could provide the necessary resolution to match the filtered sea surface field. The added resolution will help determine the nature of crustal magnetizations which give rise to the intermediate wavelength field.

From an analysis of Magsat and the sea surface field we have found that remanent magnetization is an important component over the oceans. Crustal deformation and plate motions therefore result in magnetization vectors which differ significantly from the present day field directions. Induced magnetization or VRM are important components over the oceanic plateaus and spreading centers.

Areas of study which will profit from the development of a filtered surface field and the acquisition of low altitude satellite data include the diagenesis of the oceanic crust away from the spreading centers, paleointensity of the geomagnetic field, crustal deformation and crustal heterogeneity.

N86-12863

LITHOSPHERIC STRUCTURE IN THE PACIFIC GEOID

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The high degree and order ($n,m > 12,12$) SEASAT geoid in the central Pacific correlates closely with the structure of the cooling lithosphere. Relative changes in plate age across major fracture zones in relatively young ($\lesssim$ 80 Ma) seafloor frame the east-west trending pattern formed by the geoid anomalies (Figure 1). The separation of the major fracture zones is ~1000 km, whereas the dominant wavelength of the geoid field is ~2000 km in the north-south direction.

Investigators customarily remove the effects of regional lithospheric thermal subsidence from bathymetry to expose anomalies in depth. This field removal in bathymetry corresponds to removal of some of the low degree and order ($n,m \leq 12,12$) geoidal components, and the step-like structure across fracture zones is also removed. We have, instead, removed the regional thermal subsidence from the bathymetry by subtracting a mean subsidence surface from the observed bathymetry. This produces a residual bathymetry map (Figure 2) analogous to the usual residual depth anomaly maps. The residual bathymetry obtained in this way then contains shallow depths for young seafloor, and larger depths for older seafloor, thus retaining the structure of the lithosphere while removing the subsidence of the lithosphere.

In order that sub-lithospheric density variations be revealed with the geoid, the regional geoid anomalies (~2 m) associated with bathymetric variations, must first be removed. We have used spectral techniques to generate a synthetic geoid (Figure 3) by filtering the residual bathymetry assuming an Airy-type isostatic compensation model. We have assumed a value of 100 km for the thickness of the lithosphere, and have also assumed the plane approximation to be valid. The resulting field fairly closely resembles in pattern the observed geoid of Figure 1, but the amplitudes are different, and may yet need to be adjusted through the depth of compensation and density structure. It is, nevertheless, clear that this field due to lithospheric structure may be a major component of the geoid in this region.

A comparison of the observed admittance with model admittances shows that, for the region under study, no single compensation mechanism will explain all of the power in the geoid. Our values of the admittance for the shorter wavelengths ($\lambda \lesssim 450$ km) agree with the values obtained by Sandwell & Poehls (1980) for a similar region in the Pacific assuming an Airy model. The longer wavelengths do not agree with the Airy model, nor do they agree with the thermal compensation model. This may most likely be due to the fact that the spectral contributions from the Hawaiian swell and from the regional Pacific bathymetry are indistinguishable in the frequency domain. Nevertheless, because topographic features are mainly coherent with the geoid, to first order an isostatically compensated lithosphere cut by major E-W fracture zones accounts for most of the power in the high degree and order SEASAT geoid in the central Pacific.

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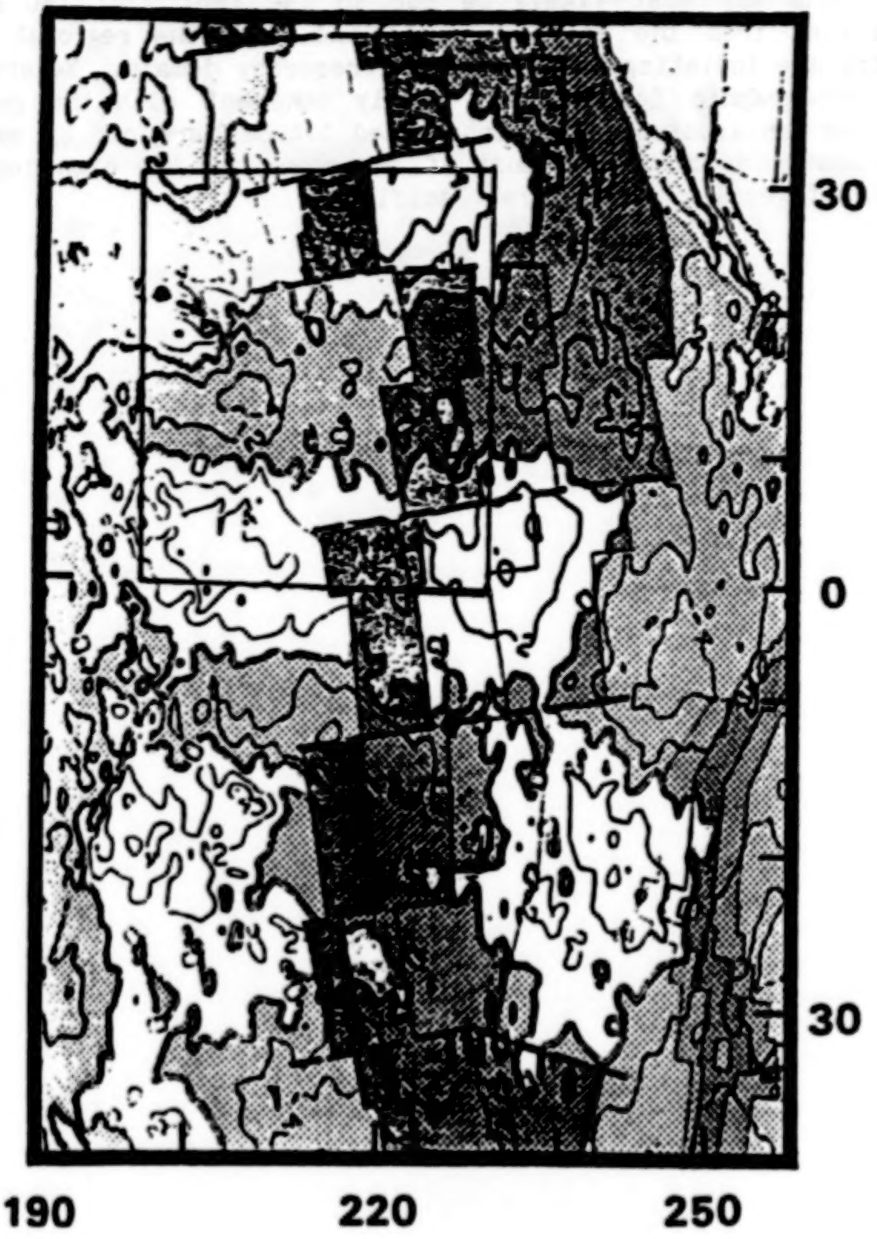

Figure 1. The SEASAT geoid superimposed on the map of the age of the ocean basins of Pitman et al. (1974). Major fracture zones with large offsets have been marked with dashed lines. From north to south, these fracture zones are Mendocino, Murray, Molokai, Clipperton, and Marquesas and the last is apparently unnamed. These fracture zones frame the pattern of geoid anomalies, and there is a correlation between regions of relatively young seafloor and positive geoid anomalies.

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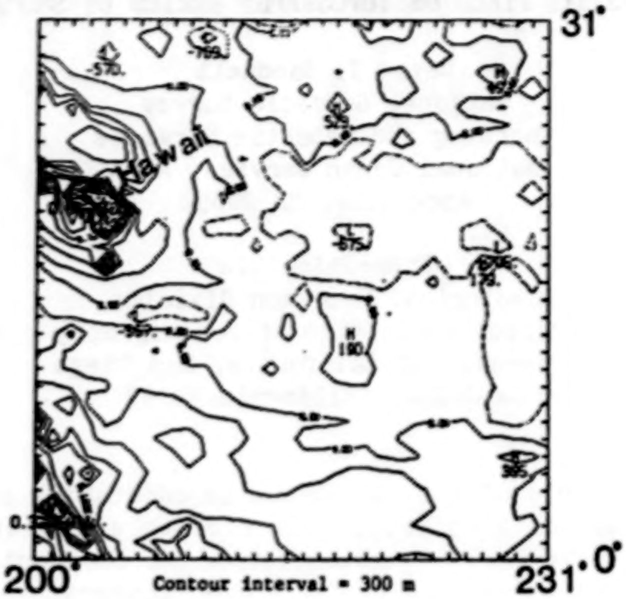
31°
Hawaii
200°
Contour interval = 300 m
231°
0°

Figure 2. The residual bathymetry obtained by removing a mean thermal subsidence surface from the observed bathymetry. Large positive values occur over shallow, young seafloor, and large negative values over deep, older seafloor.

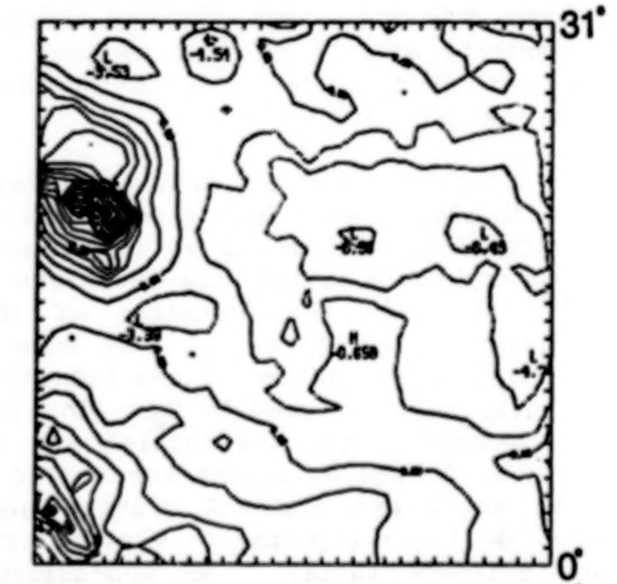
31°
200°
Contour interval = 2 m
231°
0°

Figure 3. The synthetic geoid obtained by filtering the residual bathymetry in Figure 2 through an Airy-type isostatic compensation model.

N86-12864

THE GRAVITY FIELD OF TOPOGRAPHY BURIED BY SEDIMENTS

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The gravity field of the continents is constantly changing because of mass redistribution associated with erosion and sedimentation. To understand just the effect of sedimentation on the continental gravity field, we investigated the gravity field over topography in the Northern Indian Ocean that was completely buried by sediments of the Bengal Fan.

An isopach map made from the seismic reflection and refraction in the Bay of Bengal shows two prominent N-S trending features in the basement topography. One is the northernmost portion of the Ninetyeast Ridge which is totally buried by sediments north of 10°N. The other buried ridge trends roughly N-S for 1400 km at 85°E to the latitude of Sri Lanka and then curves toward the west. It has basement relief up to 6 km. Two free-air gravity anomaly profiles across the region show a strong gravity low (~ -60 mGal) over the 85°E Ridge, while the Ninetyeast Ridge shows a gravity high.

To interpret the negative free-air gravity anomaly over the 85° ridge, we model the lithosphere as a thin elastic plate and calculate its flexural and gravitational response to an uneven sediment load. A plausible formation history for a buried ridge consists of at least two major episodes. The first is the formation of the ridge on a lithosphere with a flexural rigidity of D_1. At some later time the ridge is buried by an influx of sediments, the lithosphere is cooler, and the flexural rigidity has increased to D_2. The character of the gravity field depends primarily upon the initial and final values of flexural rigidity. These D_1 and D_2 values are varied to obtain good agreement between the model and observed gravity anomalies. Best fitting models have a 180 times increase in flexural rigidity between ridge formation and sediment burial. An approximate relationship between flexural rigidity and crustal age shows that the 85°E Ridge was formed on relatively young lithosphere, 5-15 m.y. old and that it was buried when the lithosphere was 40-80 m.y. old.

N86-12865

GRM CRUSTAL MAGNETIC ANOMALIES: SEPARATING THE LORD HOWE RISE AND NORFOLK RIDGE SUBMARINE STRUCTURES

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The high elevation of MAGSAT and POGO data makes difficult the interpretation of observed crustal magnetic anomalies in regions of any geologic complexity. In average scalar maps this is not just a matter of resolution but is also compounded by the overlap of central and flanking anomalies from nearby sources. This overlap is a function of the strength and separation of the sources and the geomagnetic latitude. Even in reduced-to-pole (RTP) maps where geomagnetic latitude effects are minimized and anomalies are located directly over their sources, overlap of anomalies will occur for nearby sources. Given the general complexity of the Earth's crustal geology, multiple source bodies will often lie within the resolution element of the MAGSAT and POGO data. Small weak sources lying near larger stronger sources will tend to be missed, although they do contribute to the total observed anomaly. Lower elevation magnetic anomaly surveys such as GRM will alleviate this problem through the combined effects of significantly greater resolution and stronger signal amplitude. This will permit not only the detection of smaller source bodies, but also analysis of their structure and nature.

The improvement a GRM would provide can be easily demonstrated in the Lord Howe Rise/Norfolk Ridge area east of Australia, between the Tasman Sea and South Fiji Basin. These submarine features are of interest because their origin has important plate tectonic implications. The Lord Howe Rise (LHR) is a continental fragment broken off from Australia by the opening of the Tasman Sea. It is a wide, shallow structure lying between 160 and 165°E longitude at 23 to 37°S latitude (Figure 1). Seismic refraction data show the LHR crust extending to depths in excess of 20 km. By contrast the Tasman Sea oceanic crust is only about 6 km thick reaching a depth of less than 11 km below sea level.

The nature of the adjacent Norfolk Ridge (NR) is less certain. This narrow N-S trending feature lies along 168°E longitude and averages less than 1° across (as defined by the 2000 m bathymetric contour). It is separated from the LHR by the New Caledonian Basin which itself is at most 3° wide. There are some similarities in the crustal structure of the NR and LHR: both have depth-to-Moho of more than 20 km, and both have a central crustal layer with seismic velocity (V_p) of 6.0-6.2 km/sec overlying a 6.7-6.8 km/sec lowest layer.

The narrowness of the NR and its close proximity to the much larger LHR (Figure 1) mean that presently available 2° average scalar magnetic anomaly maps will not be able to separately resolve these two structures. The NR has only 15% the volume of the LHR, so even if they had identical magnetic structure, the Norfolk Ridge would be a minor contribution to the anomalies shown in 2° average maps. This is born out in the observed MAGSAT and POGO data (Figure 2) which show a prominent double-lobed positive anomaly located over the LHR. At MAGSAT elevation (~450 km) under local magnetic field conditions (~54,000 nT at the surface) the peak anomaly is ~9 nT (Figure 2a). The RTP POGO data (Figure 2b) is at an elevation of 500 km and a constant main field of 50,000 nT. The peak anomaly is only 7 nT, but note that the anomaly has shifted to lie (nearly) directly over the LHR. This is the advantage of an RTP representation: the anomaly is located directly over its source. Detailed examination of the POGO data shows that the southern lobe of the LHR anomaly does not lie directly over the topographic peak of the Rise, but is displaced eastward (toward the NR) by about 2°. This is consistent with the presence of a second magnetic anomaly source at the location of the southern NR.

In order to study the effect of elevation on the anomaly signatures over the LHR-NR area, we calculated model signatures at a range of elevations between 550 (representative of POGO data) and 150 (a low GRM elevation) km for a variety of NR models. The LHR model used was a "continental" structure with a high susceptibility lowest crustal layer (Frey, 1984, in press). This model provides good agreement with the observed POGO RTP and MAGSAT average scalar data assuming no contribution from the NR.

FIGURE 1.

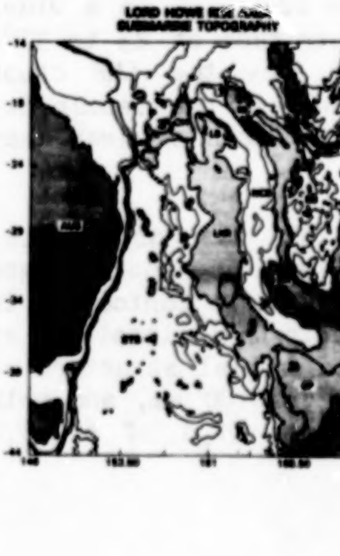
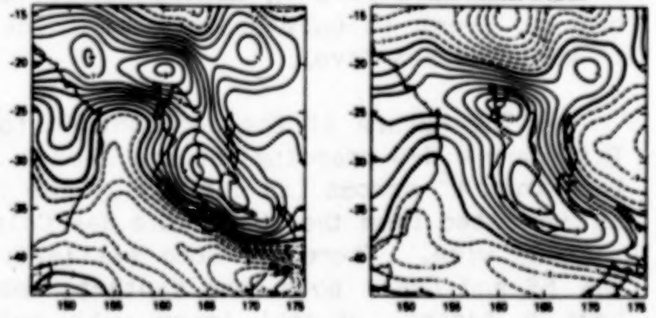


FIGURE 2.


MAGSAT AVERAGE SCALAR ANOMALIES
NORMALIZED POGO RTP ANOMALIES
-15
-20
-25

The NR structure which provides the strongest magnetic anomaly contrast with the surrounding oceanic crust is one where the NR is assumed to be thickened oceanic crust. Such a model leads to an average magnetization contrast of 1.4 A/m for the 20 km thick NR. At 550 km this structure alone produces a magnetic anomaly of only 1 nT in a vertical, 50,000 nT main field, assuming the anomaly is an induced + viscous magnetization anomaly and the magnetization contrast used represents both of these effects. By contrast, under the same conditions, theLHR model produces a +6 nT anomaly. The combined structures produce a signature somewhat different from that due to the LHR only: the southern lobe of the anomaly increases from +5 to +6 nT and the 0, 1 and 2 nT contours show a deflection toward the NR which indirectly suggests its presence. These results alone, by comparison with observed POGO RTP data, suggest the model used here for the NR is too strong a source body. The NR probably has a magnetic structure more like the LHR, with an average magnetization contrast for the NR of perhaps only 0.8 A/m with respect to its surroundings. However, it is extremely difficult to correctly infer the relative magnetic structures of the LHR and NR from these high elevation data, as many combinatons of LHR/NR structures would be capable of producing the course anomaly pattern observed.

At 450 km (a high MAGSAT elevation) there is little improvement in the NR anomaly signature. Peak values are still less than 2 nT, while the peak value for the LHR is now up to 9 nT due to the lower elevation. Eastward deflections of the anomaly contours in the combined (Figure 3a) model are again an indirect indication of the contribution of the NR to the total anomaly. These deflections are even more obvious at 350 km elevation, an optimistic best case for a limited portion of the MAGSAT data. The NR model by itself produces a 3 nT anomaly. The LHR model produces +13 and +15 southern and northern lobes, but a weak pair of -1 nT flanking anomalies also appears east and west of the LHR. The overlap of the LHR and NR anomalies pulls the combined model anomaly signature eastward into a pattern which now follows the submarine topography. At 350 km the effect at this too-strong NR structure is such that the NR would probably be recognized as the contributor, a conclusion which might have been tentatively offered based on the higher elevation data only if the NR were as strong as modeled here.

The NR is resolved as a pair of +5 nT and +3 nT anomalies in the combined model signature at 250 km. The NR structure would produce +5 and +6 nT peaks in the northern and southern portions, but overlap with the flanking negative LHR anomalies reduces the NR portion of the combined model anomaly signature.

At GRM elevations (~150 km) the NR structure is clearly resolved (Figure 3b). The LHR and NR are each separately overlain by positive anomaly signatures that are individually closed. A -6 nT anomaly lies over the New Caledonian Basin between the LHR (peak anomaly >63 nT) and

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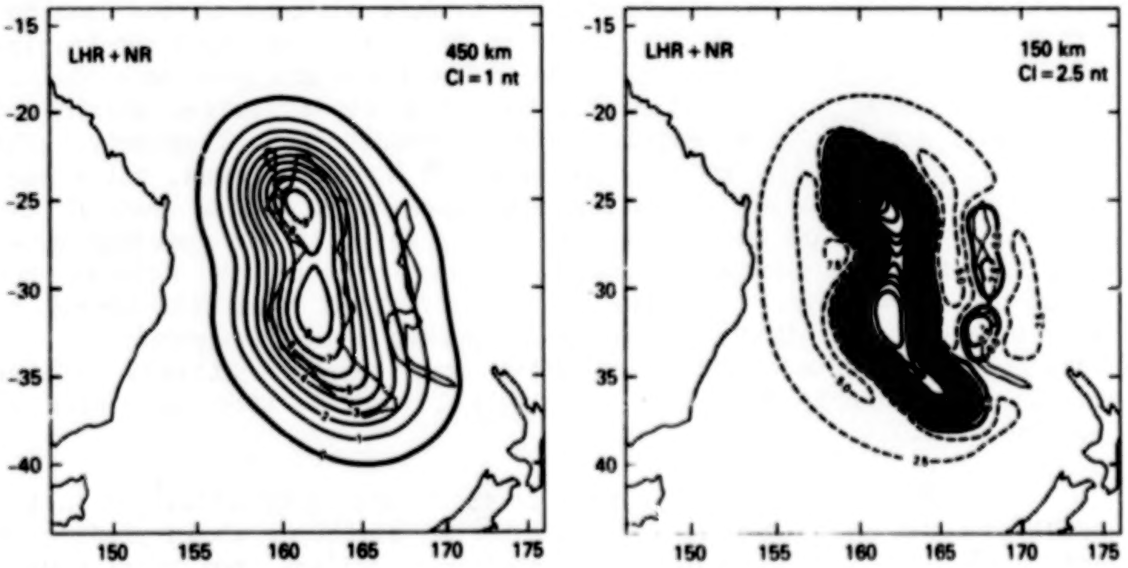
the NR (>11 nT). The ratio of peak amplitudes between the NR and LHR is slightly greater than the volume ratios, consistent with the differences in magnetic structure used in the models. The detailed NR structure is also revealed by the anomaly pattern, showing the slight enlargement and westward displacement of the NR at 167°E, 32°S. With data at this elevation it would be possible not only to separately resolve the LHR and NR and to determine their relative magnetic structure, but also to look at variations in that structure throughout the NR or LHR. This would be true not only for this too-strong NR model, but also for the case where the NR had a magnetization contrast with respect to its surroundings equal to or somewhat weaker than that of the LHR.

FIGURE 3. Lord Howe Rise/Norfolk Ridge Model Anomaly Signatures



N86-12866

SEA FLOOR SWELLS AND MANTLE PLUMES

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Most of the intraplate oceanic hot spots are located on the crest of broad topographic swells in the sea floor. These swells have Gaussian-shaped profiles, with up to 1.6 km of relief and half-widths of 200-300 km. Swells are accompanied by positive geoid height anomalies with amplitudes of 6-8 m. In the Atlantic and Pacific basins alone, swells cover an area equal to 10% of the earth's surface. Next to boundary layer contraction, swells are the most important cause of uplift and subsidence in oceanic lithosphere.

Calculation of buoyancy-supported topography and geoid height have been combined with uplift data from laboratory experiments to assess whether sea floor swell can be produced by mantle plumes. The critical constraints are: (i) swell topographic profiles, (ii) geoid height/topographic height ratios, and (iii) uplift rates, estimated to be 0.2 km/ma.

The laboratory experiments, made in strongly thermo-viscous glucose solutions, give information on the characteristics of mantle plumes. The morphology of low viscosity plumes is governed by their interaction with mantle convection. In a convective environment, elongate, continuous plumes are subject to Whitehead instabilities. They break up into chains of nearly spherical Stokes blobs. The blobs rise steadily through the asthenosphere, then decelerate and collapse as they reach the base of the lithosphere. The free surface swells rapidly as the plume approaches the lithosphere, reaches a maximum height, and then subsides on a slow time scale as the plume collapses. At maximum elevation the swell profile is approximately Gaussian. The swell crest relaxes first, producing, during the subsidence phase, a plateau-like topography. It is found that the maximum swell height depends on the thickness of the lithosphere. The maximum swell is approximately the same as predicted for uplift in an isoviscous half space, provided that the plume diameter exceeds the lithospheric thickness. Uplift is reduced if lithospheric thickness exceeds the plume diameter.

Experimentally determined plume ascent and collapse histories are scaled to mantle conditions and are used as input for calculations of the time evolution of sea floor swells. The uplift is calculated for a model consisting of an isoviscous half space capped by an elastic lid, using a Green's function approach. A comparison with data from the Hawaiian Swell and the Bermuda Rise indicates that, in order to support these swells, spherical mantle plumes must be 300-350 km in diameter and must have negative density anomalies of approximately 2%. With these characteristics, mantle plumes ascend at 20 cm/a and generate 1.5 km of uplift in 6 ma. The most difficult constraint to satisfy are the observed geoid/topography ratios, which require a low density source at 50-70 km depth. The ability of mantle plumes to reach these depths by viscous flow depends on the creep rheology of the lower lithosphere. Plumes can creep to 60 km depth in 90 ma old lithosphere if the creep activation energy E^* is less than 50 kcal/mole. If $E^* = 100$ kcal/mole, plumes cannot creep above 90 km depth in old lithosphere. In that case some additional mechanism for eroding the lithosphere is needed.

IV. General Lithosphere

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N86-12867

PROPERTIES OF THE LITHOSPHERE AND ASTHENOSPHERE DEDUCED FROM GEOID OBSERVATIONS

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Data from the GEOS 3 and SEASAT Satellites have provided a very accurate geoid map over the oceans. Broad bathymetric features in the oceans such as oceanic swells and plateaus are fully compensated. For these features it can be shown that the geoid anomalies due to the density structures of the lithosphere are proportional to the first moment of the density distribution. The deepening of the ocean basins is attributed to thermal isostasy. The thickness of the oceanic lithosphere increases with age due to the loss of heat to the sea floor. Bathymetry and the geoid provide constraints on the extent of this heat loss. Offsets in the geoid across major fracture zones can also be used to constrain this problem. Geoid-bathymetry correlations show that the Hawaiian and Bermuda swells and the Cape Verde Rise are probably due to lithospheric thinning.

Under some conditions the surface gravitational potential or acceleration can be related to the one-dimensional distribution of density beneath the point of measurement. One example of such a relationship is the Bouguer formula for the surface gravity anomaly. The Bouguer formula relates the surface gravity anomaly to the source density distribution beneath the point of measurement. It is valid if the mass anomaly is shallow and is slowly varying in the horizontal directions. If the near surface density distribution is isostatic the gravity anomaly given by the Bouguer formula is zero but the first moment of the density distribution can be related to the local potential and geoid anomalies. Thus the geoid anomaly can be directly related to the dipole distribution of density beneath the point of measurement if the condition of isostasy is applicable and if the geoid anomaly is caused by slowly varying near surface density variation.

Many of the observed geoid anomalies can be explained directly using the relationship between the geoid anomalies and the dipole density distribution. The positive geoid anomalies associated with the mid-ocean ridge system are consistent with thermal isostasy. However, the direct correlation between the geoid and bathymetry is noisy due to the geoid anomalies of deeper origin. Another approach to the study of geoid anomalies associated with ocean ridges is to utilize the geoid changes across major fracture zones. Major fracture zones are generated by transform faults on the ocean ridge system. Thus the ocean floors on the two sides of a fracture zone have age differences that are related to the offsets in the ridge at the transform fault that generates the fracture zone. The age difference can be determined from the sea floor magnetic anomalies.

Systematic correlations of geoid and bathymetry have also been found for oceanic swells. These are near circular regions of anomalously shallow bathymetry with a radius of 500-1000 km. Examples include the Hawaiian swell that surrounds the active volcanic center at the end of the Hawaiian island and seamount chain and the Bermuda swell. The good correlation can be explained by Pratt compensation with a 100 km depth of compensation. A physical mechanism that would appear to explain this correlation would be lithospheric thinning. Normal oceanic lithosphere has a thickness of about 100 km so that thinning of this lithosphere would have a depth of compensation of about this value. The observed correlation would appear to preclude any association of the geoid and gravity anomaly over the Hawaiian swell with mantle convection. If there is a mantle plume beneath Hawaii with a deep structure it does not appear to have an effect on the geoid.

A relatively simple model for rifting and mountain formation can be developed by introducing crustal and lithospheric thinning factors. The condition of isostasy and the measurement of the geoid constrains the two thinning factors. This approach appears promising for the study of sedimentary basins and major mountain belts.

N86-12868

SUBDUCTION DYNAMICS: CONSTRAINTS FROM GRAVITY FIELD OBSERVATIONS

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At present, satellite systems do the best job of resolving the long-wavelength components of the earth's gravity field. Over the oceans, satellite-borne radar altimeters such as SEASAT provide the best resolution observations of the intermediate-wavelength components ($4000 \text{ km} > \lambda > 200 \text{ km}$). It is, therefore, not surprising that satellite observations of gravity have contributed substantially to our developing understanding of the dynamics of subduction. Recall that large, long-wavelength geoidal highs generally occur over subduction zones. These highs are attributed to the superposition of two effects of subduction: (i) the positive mass anomalies of subducting slabs themselves, and (ii) the surface deformations such as the trenches (largely negative mass anomalies) convectively inducted by these slabs as they sink into the mantle. Models of this subduction process suggest that the mantle behaves as a non-Newtonian fluid, i.e., its effective viscosity increases significantly with depth, and that large positive mass anomalies may occur beneath the seismically-defined Benioff zones.

Interpretation of intermediate-wavelength gravity or geoid anomalies over subduction zones remains a problem. In order to solve this problem lithospheric and crustal effects must be carefully separated from those of flow-induced surface deformation. GRM should provide a large amount of new information about the intermediate-wavelength component of the gravity field particularly over continents such as Asia and South America which lack surface gravity coverage. Note that these two continents are bordered by major subduction/convergence zones.

Future satellite gravity missions such as GRM, Topex, Geosat and/or their successors could resolve temporal variations in the gravity field. In particular, the earthquake deformation cycle at convergence zones, specifically the major dip-slip earthquakes should give rise to variations in the geoid which have amplitudes as large as 5 cm or even more and wavelengths of several hundred kilometers. Such variations are predicted by simple dislocation models. Observations of these temporal variations in the gravity field could prove useful; they should not be overlooked in designing future satellite gravity missions.

N86-12869

CONTINENTAL AND OCEANIC MAGNETIC ANOMALIES: ENHANCEMENT THROUGH GRM

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Earth-orbiting satellites over the past two decades have provided consistent global magnetic anomaly data sets which have given us unique insight on regional petrologic variations of the crust and upper mantle and crustal thickness and thermal perturbations. Verification of the satellite magnetic data has been demonstrated by quantitative comparisons with aeromagnetic anomalies of the conterminous U.S. and western Canada. In contrast to the POGO and MAGSAT satellites, the GRM satellite system will orbit at a minimum elevation to provide significantly better resolved lithospheric magnetic anomalies for more detailed and improved geologic analysis. In addition, GRM will measure corresponding gravity anomalies to enhance our understanding of the gravity field for vast regions of the earth which are largely inaccessible to more conventional surface mapping. Crustal studies will greatly benefit from the dual data sets as modeling has shown that lithospheric sources of long-wavelength magnetic anomalies frequently involve density variations which may produce detectable gravity anomalies at satellite elevations. Furthermore, GRM will provide an important replication of lithospheric magnetic anomalies as an aid to identifying and extracting these anomalies from satellite magnetic measurements.

After the question of the formation of the earth itself, the most fundamental problem of the geosciences concerns the origin and characterization of the continents and oceans. An essential difference in the earth is between the continents and oceans which is reflected in gravity via the Bouguer anomaly. However, as in the case of free-air and isostatic gravity anomalies, satellite magnetic measurements indicate no overwhelming difference between these regions. This is illustrated in Figure 1 which shows scalar 2°-averaged MAGSAT anomalies differentially reduced to the radial pole of intensity 60,000 nT at 400 km elevation for the eastern Pacific Ocean, North and South America, the Atlantic Ocean, and Euro-Africa. These radially polarized anomalies have been adjusted for differential inclination, declination and intensity effects of the geomagnetic field, so that in principle these anomalies directly reflect the geometric and magnetic polarization attributes of crustal magnetic sources. Characteristics of the data given in Figure 1 include the amplitude range (AR), amplitude mean (AM), contour interval (CI), and the normalization amplitude (AMP) for the radially polarizing field.

A subtle indication of the difference between oceans and continents is obtained by computing mean magnetic anomalies for the region shown in Figure 1. The analysis indicates that the mean magnetic anomaly of the continents (0.3 nT) is greater than the average for the oceans (-1.8 nT). This observation is compatible with the shallow crust of the ocean basins and evidence that suggests that the Moho is a magnetic boundary between crustal magnetic and upper mantle non-magnetic rocks. However, this result may be muted by remanence effects which for regional crustal magnetic sources are generally not well known and at MAGSAT elevations are not well resolved.

Low-level observations of the oceans indicate that most of the magnetic anomalies reflect the age of the crust and are caused by the acquisition of remanent magnetization in the reversing magnetic field as the rocks pass through their Curie Point. However, as shown in Figure 1, only the broader scale Mesozoic and Cretaceous quiet zones seem to be clearly affiliated, respectively, with pronounced negative and positive radially polarized anomalies at MAGSAT elevations. In contrast, the satellite elevation magnetic anomalies of the continents seem to have a predominance of induction effects. There are remanent effects, but these are characteristically high wavenumber anomalies and are attenuated at higher elevations in the continental areas. The increased anomaly resolution derived from GRM's 160 km elevation orbits will significantly contribute to an understanding of the role which remanence has in causing regional anomalies of the oceans and continents.

Continental satellite magnetic data show an apparent sharp truncation and even parallelism of the anomalies along the leading edges of the North and South American plates, whereas across trailing plate continental margins prominent anomalies tend to continue into the ocean. Detailed analysis of the MAGSAT orbital data for South America indicates that the trailing edge anomalies have no apparent relationship to external fields, so these anomalies appear to be internally derived. Many of these anomalies show a striking parallelism with the tracks of hotspots particularly in the south Atlantic, although there is little consistency in the sign of the radially polarized anomalies and the hotspot tracks. Gravity and bathymetric correlations also suggest possible affiliation of some of these anomalies with subsided continental fragments. Clearly, information on these features is very limited and their origin is an important area of inquiry. High resolution magnetic data and correlative gravity anomalies provided by GRM will significantly facilitate understanding their origin and possible role in the evolution and dynamics of the continents and oceans.

The radially polarized anomalies of Figure 1 permit testing the reconstruction of the continents prior to the origin of the present day Atlantic Ocean in the Mesozoic Era. Indeed, as demonstrated in Figure 2, the radially polarized MAGSAT anomalies of North and South America, Euro-Africa, India, Australia and Antarctica exhibit remarkably detailed correlation of regional magnetic crustal sources across rifted margins when plotted on a reconstruction of Pangea. Obviously, these results suggest great ages for the geologic conditions which these anomalies describe and provide new and fundamental constraints on the geologic evolution of the continents. The high-resolution regional magnetic and correlative gravity anomaly data potentially available from the GRM offer the clear promise to improve quantitative geologic modeling of these features and to detail their development through geologic time.

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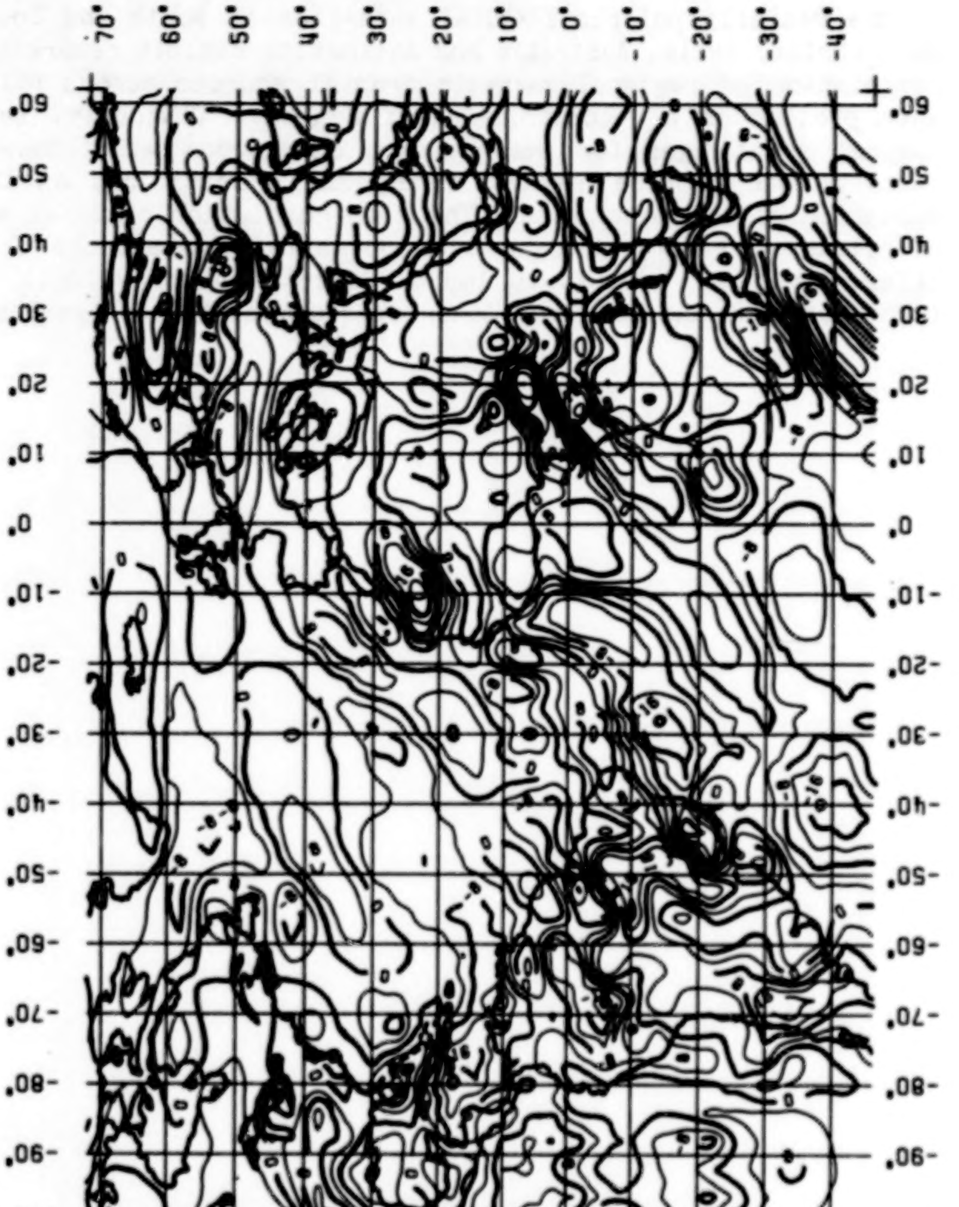
FIGURE 1

RADIALLY POLARIZED $\langle Z^{P} \rangle$ MAGSAT MAGNETIC ANOMALIES

Z = 400 km AMP = 60,000 nT

AR = (32.8, −25.1) nT CI = 4 nT AM = −0.8 nT


70°
60°
50°
40°
30°
20°
10°
0°
-10°
-20°
-30°
-40°
60°
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40°
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10°
0°
-10°
-20°
-30°
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-50°
-60°
-70°
-80°
-90°
-100°
-110°
-120°
-130°
-140°

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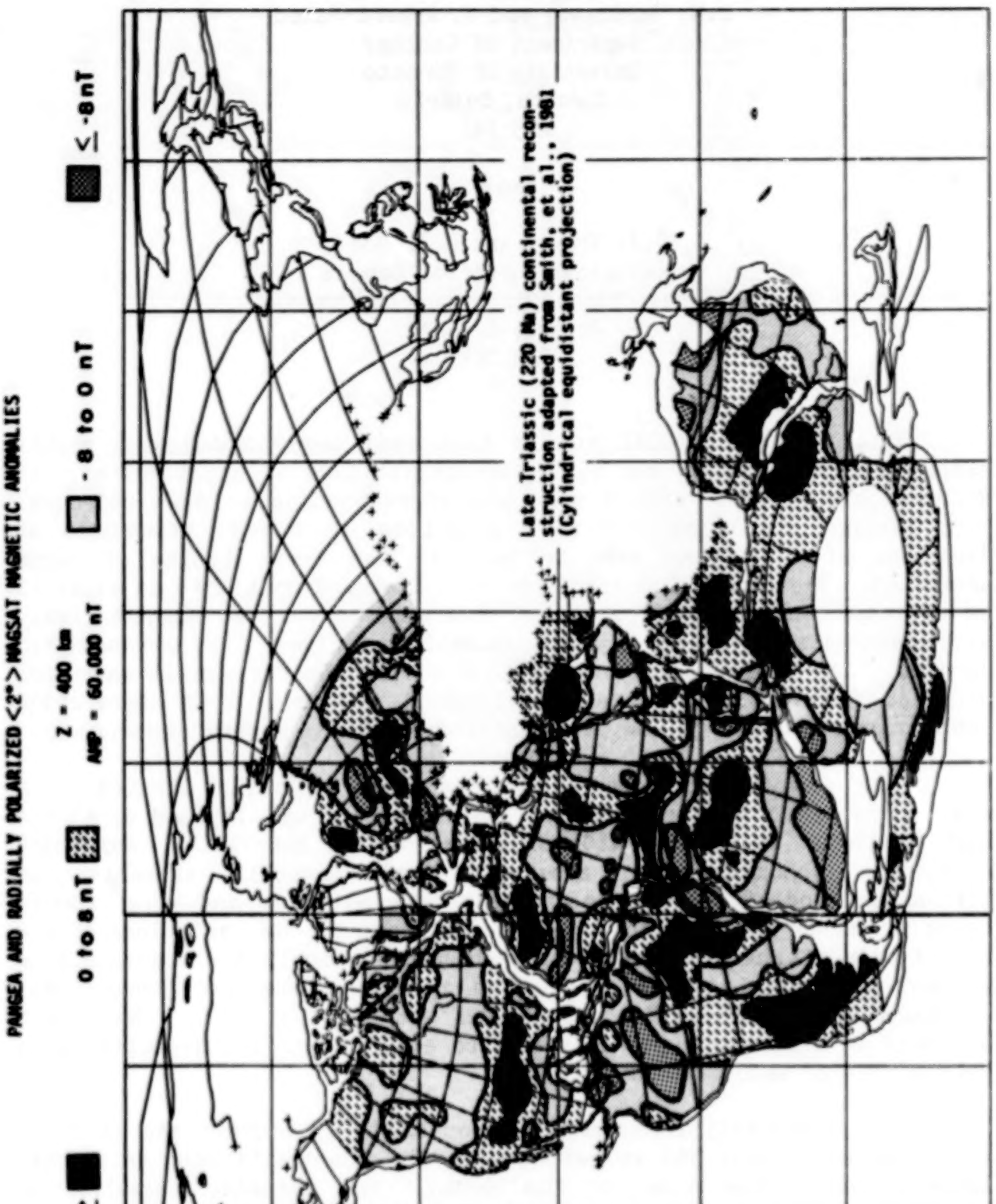
FIGURE 2



PANGEA AND RADIALLY POLARIZED <2°> MAGSAT MAGNETIC ANOMALIES

Z = 400 km
AMP = 60,000 nT
■ ≥ 8 nT
▨ 0 to 8 nT
☐ -8 to 0 nT
▩ ≤ -8 nT
Late Triassic (220 Ma) continental reconstruction adapted from Smith, et al., 1981 (Cylindrical equidistant projection)

N86-12870

THE RESOLUTION OF A MAGNETIC ANOMALY MAP EXPECTED FROM GRM DATA

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Data from the MAGSAT mission have been used to derive a global scalar magnetic anomaly map at an average altitude of about 400 km. It was possible to work with 2 data sets corresponding to dawn and dusk. This enabled us to identify those anomalies which were repeatable at dawn and at dusk, and also to estimate the error limits of these anomalies. The repeatable anomalies were downward continued to about 10 km altitude. The anomalies over Canada were correlated quantitatively with band-pass filtered magnetic anomalies derived from aeromagnetic surveys. The close correlation indicates that the repeatable anomalies detected from orbit are due to geological causes. This correlation lends support to the geological significance of the global anomaly map.

The downward continued anomalies were typically limited to a scale size of 500 km or greater. The limitation was imposed by a) the high altitude (a range of 280 to 560 km) of the satellite. Any short wavelength (shorter than about 500 km) magnetic anomalies of lithospheric origin were attenuated at this altitude and were reduced below the error limit of the original data, and b) the variations of the satellite's altitude, which created elongated anomalies along satellite passes, analogous to the flight-line leveling noise of conventional aeromagnetic surveys. The noise level was about ± 2 nT. The filter employed in order to suppress the noise also suppressed anomalies with wavelengths of about 900 km or less.

The geopotential research mission (GRM) will orbit the earth at an altitude of about 160 km, with relatively minor altitude variations, largely due to the shape of the earth. The magnetic anomalies of lithospheric origin will be enhanced by a factor of about 4 because of the lower altitude of GRM compared to that of MAGSAT. The flight-line leveling noise will probably be reduced to below ± 1 nT, allowing us to retain relatively shorter wavelengths in the derivation of a magnetic anomaly map. This will increase the magnitude of the anomalies and also significantly enhance the resolution of the map. We can expect an overall improvement of about an order of magnitude in the magnetic anomalies derived from GRM data compared to those deduced from MAGSAT data.

A possible resolution of a magnetic anomaly map expected from GRM data is estimated from the upward continuation to 160 km of a high-pass filtered magnetic anomalies of the Canadian shield derived from low-level aeromagnetic surveys. The filter reduces the long wavelengths which overlap with the main geomagnetic field, since they may have been dominantly contaminated by the field. The upward continued anomalies have high resolution and delineate major geological features. It is concluded that a magnetic anomaly map derived from GRM data will have the ability to detect geological features as small as about 100 km in scale.

V. Mantle Convection

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THE IMPORTANCE OF GRM GRAVITY OBSERVATIONS IN CONTINENTAL REGIONS

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Fifteen years ago most geophysicists believed that the major hot upwelling regions in the upper mantle were beneath ridge axes. It slowly became apparent that this view was not compatible either with our understanding of the fluid dynamics of convection at high Rayleigh numbers, or with the evolution and structure of spreading ridges. Both lines of reasoning required the geographical position of the ridges to be independent of the circulation below, which should consist of a number of rising and sinking regions whose horizontal scale is small compared with that of the larger plates.

These ideas were not widely accepted until the two altimetric satellites clearly showed the existence of gravity anomalies with wavelengths between 1500 km and 3000 km which correlated with residual depth anomalies. More recently Haxby and Weissel have suggested that there is also an even smaller scale convective circulation with a wavelength of less than 500 km. Numerical experiments and Seasat profiles demonstrate that similar small scale circulation must also exist near fracture zones. The mantle therefore must contain at least three scales of circulation. One is comparable to the plate dimensions, known as the large scale circulation, which returns material from the Island arcs to the ridges. Another of an intermediate scale comparable to the depth of the upper mantle and a third with a small scale comparable to the thickness of the asthenosphere. This picture has been established using observations of gravity and bathymetry in oceanic regions. It is not yet clear whether the circulation beneath the continents is similar to scales of circulation beneath the continents. The orbit will not be low enough to detect the small scale circulation. Also the amplitude and wavelength of flexural and other plate signals will be comparable to that of the intermediate scale of the circulation, from which it will not be possible to separate them without additional information. It is important to map the mantle circulation beneath the continents because its evolution can then be easily and cheaply investigated by field geologists. Such studies are severely limited by cost in oceanic regions.

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THE SOURCE OF THE EARTH'S LONG WAVELENGTH GEOID ANOMALIES: IMPLICATIONS FOR MANTLE AND CORE DYNAMICS

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The long-wavelength ($\ell \lesssim 10$) components of the Earth's gravity field result mainly from density contrasts associated with convection in the mantle. However, direct interpretation of the geoid in terms of mantle convection is complicated by the fact that convective flow results in dynamically maintained deformation of the surface of the Earth, the core-mantle boundary (CMB), and any interior chemical boundaries which might exist. (Mid-ocean ridges and deep sea trenches are familiar examples of surface topography resulting from density contrasts of convective origin.) These boundary deformations have effects on the geoid opposite in sign and comparable in magnitude to those of the interior density contrasts driving the flow; thus the total geoid anomaly in a dynamic earth is a small number resulting from the difference of two relatively large quantities.

We have calculated the total geoid response for interior density contrasts as a function of depth and spherical harmonic degree for a series of simple mantle flow models. These models assume a self-gravitating, incompressible fluid with a spherically symmetric, radially layered Newtonian rheology. We consider models both with mantle-wide flow and with chemical stratification between the upper and lower mantle. For a given density contrast, the sign of the total geoid anomaly depends on the variation of viscosity with depth; uniform viscosity, or viscosity decreasing with depth, leads to negative total geoid anomalies for positive density contrasts due to the overwhelming effect of deformation of the upper boundary, while a sufficiently large increase in viscosity with depth results in a total positive anomaly. The amplitudes of the net geoid anomalies get smaller the closer the driving density contrasts get to a boundary. Density contrasts at compositional boundaries are identically compensated and lead to zero net geoid anomalies. For a given density contrast, geoid anomalies are generally much smaller for a chemically stratified mantle than for one of uniform composition. Density contrasts of different wavelengths sample the mantle in different ways, allowing resolution of variations of mantle viscosity with depth if the driving density contrasts can be determined by some other method.

Recent advances in seismic tomography have resulted in images of long-wavelength lateral heterogeneity in seismic velocity. These velocity variations presumably are proportional to density variations, both resulting from temperature differences associated with mantle convection. Using the results from seismic tomography, a geophysical model of subducting slabs, and the effects of Pliestocene deglaciation, in conjunction with the dynamic geoid response for flow models allows us to account for 90% of the variance in the observed long-wavelength (ℓ = 2-9) nonhydrostatic geoid.

This successful explanation of most of the long-wavelength geoid using seismically imaged density contrasts and dynamic flow models has implications for a wide range of problems in mantle and core dynamics:

- Flow models that successfully predict the geoid have several kilometers of dynamically maintained relief at the CMB. This topography, which correlates well with the geoid, may have an important effect on core dynamics and on core-mantle coupling.
- There is substantial agreement between the thermal structures of the upper and lower mantle. Surface hotspots lie above hot regions of the lower mantle and cold lower mantle is associated with subduction in the upper mantle. Either convection is mantle-wide or thermally coupled.
- For mantle-wide flow, about a kilometer of dynamically maintained surface topography is predicted. The pattern and amplitude approximately match observed oceanic depth anomalies and continental hypsographic anomalies. Changes in positions of continents and ocean basins relative to the mantle convection pattern would result in substantial epeirogenic motions and changes in eustatic sea level.
- By interpreting the seismically imaged density anomalies in terms of temperature contrasts, we can use the flow models to calculate the advected heat flux through the lower mantle. By comparing this to the observed global heat flux we conclude that the viscosity of the lower mantle exceeds 10^{23}p.
- Our preferred viscosity model has a 10^{21} p asthenosphere, with viscosity increasing to 3×10^{23} p in the lower mantle. In addition to explaining the geoid, such a model satisfies the relaxation spectra for Fennoscandia, the geoid anomaly over Hudson Bay and the long relaxation time for J_2. Observations of the rates of change of other long wavelength components of the Earth's gravity field would provide powerful tests of this model.

At present we can explain 90% of the variance in the geoid at long wavelengths. Expected improvement in seismological techniques and computation of the geoid response for more realistic rheologies should allow further improvement. Accurate determination of long-wavelength geoid anomalies in conjunction with these developments should greatly advance our knowledge and understanding of mantle convection and the driving mechanism for plate motions.

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INTERPRETATION OF THE GEOID

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That there were long wavelength non-hydrostatic components in the Earth's gravitational field was first suggested by Jeffreys who fitted 2,000 determinations of g over continents and oceans by spherical harmonics up to, and including, the third degree terms. He found 10-20 mgal anomalies --- negative over the Indian Ocean and the Caribbean and positive over Europe and the West Pacific. It had been taken as an axiom that only short wavelength anomalies existed, so that his discovery was widely discounted because of the poor global distribution of his data. His view was however vindicated by the first satellite observations. On superposing the first satellite geoid determined by Iszak upon Ootilla's geoid which was based, as Jeffreys, on surface gravity determinations (both of which included 4th degree terms), good agreement was observed except over the Pacific area of the globe (Runcorn, 1965). The poor agreement over the Pacific was interpreted as the result of inadequate observations there. Many geoids were determined from satellite observations, including Doppler measurements, and workers in this field followed Jeffreys in their explanations, i.e., that the geoid was the result of density differences in the mantle maintained since the primeval Earth by its finite strength. Various models based on this assumption were developed.

To explain continental drift, I had to find a different explanation for the geoid and proposed (Runcorn, 1963, 1964, 1965, 1966, 1967a) that the geoid is caused by the density anomalies which provide the buoyancy forces driving convection. I showed that the acceleration, inertia and Coriolis terms in the Navier-Stokes equation for mantle flow were negligile compared with the viscous term, assuming the flow velocities are of the order of those for continental drift. The long wavelength gravity anomalies are of the order of 10^{-5} and are consistent with buoyancy forces of the order of 10^{-2} dynes/cc.

I also pointed out that the positive anomalies seemed to be associated with the trenches, a correlation which has become clearer in the more recently-determined geoids, and the negative anomalies were near the extensional features of the crust; this correlation is now known not to be particularly good.

I discussed the possibility of a mathematical connection between the geoid coefficients and the spherical harmonic components of the flow (Runcorn, 1966, 1967 a, b). Clearly the positive and negative anomalies in the geoid are associated with the descending and ascending limbs of the convection current but there has been dispute of the sign to be attached to this association. In the simplest case of constant viscosity, no slip boundary conditions and g proportional to the radius (which is nearly the case for the Moon), I had proved (Runcorn, 1967b), in explaining the Moon's figure, that the negative gravity anomaly was associated with the downgoing stream. I conjectured that in the Earth the more complex situation resulted in the opposite association. In general I argued that the balance between the extra mass associated with the upward surface distortion over the uprising current of hotter and less dense material was one which could yield either sign of the gravity anomaly depending on the conditions. In the case of the Moon the "bulge" towards the Earth is associated with positive gravity.

There is now general agreement that the low harmonics of the geoid are due to mantle convection, but how convection coupled with the plates is obscure. At first it seemed plausible to expect a close association between the ocean ridges and the upwelling mantle convection, but there was serious objection to this in respect of the ridges surrounding Africa. Plate tectonics showed that the phenomena at the ridge would result simply from the moving apart of the plates, hence the convection cells inferred from the geoid do not have a simple one-to-one correlation with the plates. The plates move, on the convection hypothesis, by the net force arising from the complex pattern of viscous drag on the lower lithosphere boundary and this can be calculated. The forces appear to be of the right magnitude and direction to initiate the breaking up of Gondwanaland, if it is supposed that the mantle convection pattern is stationary over the last 100-150 My. In this way convection seems a more profitable geophysical theory than gravity sliding, as it offers the possibility of making important use of the geoid data.

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MANTLE CONVECTION AND THE LARGE SCALE STRUCTURES OF THE EARTH'S GRAVITATIONAL FIELD

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The connection between the observed large scale structure of the earths' gravitational field, as represented by the GEM10 model, and the surface kinematic manifestations of plate tectonics, as represented by the absolute plate motion model of Minster and Jordan (1978), is explored using a somewhat novel method of analysis. Two scalar derivatives of the field of surface plate velocities, namely the horizontal divergence and the radial vorticity, are computed from the plate motion data. These two scalars are respectively determined by the poloidal and toroidal scalars in terms of which any essentially solenoidal vector field may be completely represented. They provide a compact summary of the observed plate boundary types in nature, with oceanic ridges and trenches being essentially boundaries of divergence, and transform faults being essentially boundaries of vorticity. Oceanic heat flow of course correlates extremely well with surface divergence as one would expect of a thermally forced circulation. Degree correlations of the divergence and vorticity with the field of geoid heights, reveals a rather interesting complementary structure which is suggestive of strong coupling out of the poloidal component of flow and into the toroidal component such as one would expect on the basis of mechanical arguments. The degree variance spectrum for the divergence field also very clearly reveals a strong peak at the average horizontal scale of the surface motions.

CONSTRAINTS ON THE RHEOLOGICAL STRUCTURE
OF THE MANTLE

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Rheological models of the mantle are at present limited to radial symmetry, usually with homogeneous linearly viscous, or viscoelastic incompressible layers. While such models are probably overly simple, they readily allow calculation of geophysical effects, such as post glacial rebound and related changes in the earth's shape. They are also directly applicable to problems of global mantle flow and plate motions.

Mantle viscosity was initially constrained by observations of post glacial rebound and secular changes in length of day. These have been more recently supplemented with observations of gravity anomalies, secular polar motion and changes in J_2. In addition, the association of long wavelength components of the geoid with the effects of subducted density anomalies and seismically inferred density anomalies in the lower mantle further constrains the viscosity structure.

Analytic solutions of the deformation of spherically symmetric, self gravitating sphere with incompressible, homogeneous, linearly viscous layers have been obtained in a form simple enough to allow various effects of particular models to be clearly identified. The lithosphere is represented by a purely elastic layer. Density contrasts between layers correspond to non-adiabatic density gradients in the mantle; the presence of such non-adiabatic density contrasts introduces additional modes into the relaxation spectrum, and complicates its interpretation. Such effects may account for differences among results for similar models that have appeared in the literature.

The viscosity of the lower mantle is constrained by the relaxation of the lowest degree ($\ell=2$) deformation of the mantle, which is associated with measurements of changes in l.o.d., J_2 and the rate of polar wander. The relaxation is mantle wide, and hence depends on the complete viscosity structure, as well as lithosphere thickness and rigidity. Recent determinations (by Dziewonski and Woodhouse, and Clayton and Comer) of lateral variations of seismic velocities in the lower mantle may provide another, new constraint.

Assuming that the seismic velocity variations are associated with density variations, Hager et al. have shown that they can account for most of the low degree variance in the geoid. By further assuming that the anomalies are due to temperature variations, one can calculate the convective flow field driven by the density anomalies, and the resulting advected heat flux, which is inversely proportional to the viscosity. This requires the lower mantle viscosity to be greater than $\sim 10^{23}$ poise.

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THE ROLE OF A PRESSURE-DEPENDENT RHEOLOGY IN THE DYNAMICS OF MANTLE CIRCULATION

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We have constructed a thermomechanical model for upper mantle convection such that the thickness and the structure of the lithosphere are determined self-consistently by the heat transported by convection. In this study of the interaction between the lithosphere and upper mantle, strongly temperature- and pressure-dependent rheologies for both Newtonian and non-Newtonian creep mechanisms are employed. For a strictly temperature-dependent rheology an insignificant amount of heat, less than $12.5 mW/m^2$, can be transported convectively for an interior viscosity, $0(10^{21} Pas)$, compatible with post-glacial rebound. On the other hand, for similar values of the interior viscosity, steady heat fluxes between 20 and $40 mW/m^2$ are produced by introducing pressure-dependence into the rheology. For the temperature- and pressure-dependent flow law the horizontally averaged interior temperature displays very little variation with the amount of heat evacuated, once all of the rheological parameters are fixed. This finding may have important ramifications for parameterized convection. We employ both the single-mode, mean-field approximation and the complete two-dimensional equations, using finite-elements, to obtain solutions for the various types of rheologies. From evaluating the geophysically relevant observables, such as topography, free-air gravity anomalies, surface heat-flow and stress field in the lithosphere, we find that the lateral variations of these quantities predicted by a non-Newtonian rheology are much smaller than those derived from a linear rheology. These results suggest that surface variations of geophysical observables are more compatible with a non-Newtonian rheology in the upper mantle.

We have also investigated the evolution of the oceanic lithosphere from a thermomechanical approach. The finite-amplitude development of secondary convection cells beneath the oceanic plates is studied by means of the single-mode mean-field equations and the fully two-dimensional convection equations, using finite-element techniques. Both Newtonian and non-Newtonian rheologies with highly temperature- and pressure-dependences, and an activation energy of 100 Kcal/mole have been employed. The temperature at the base of the convection medium governs the final thickness of the lithosphere. The mean interior temperature varies only slightly during the temporal evolution. Non-Newtonian rheology has the tendency to induce oscillatory time-dependent behavior in the flow structure. Heat flow, topography and gravity are influenced by secondary convection in two ways. Small scale perturbations with wavelengths of around 600 km arise from the lateral thermal differences between the uprising and descending convective limbs; large-scale features are also produced as a consequence of lithospheric growth. The calculated quantities of the heat-flow topography and gravity associated with small-scale convection are typically in the range of 0(HFU), $0(10^{2}\,\mathrm{m})$, and 0(10mgal). The horizontal mean-temperature profiles from the convection model are used to calculate long wavelength geophysical observables as a function of age. Convective processes are found to reduce the rate of lithospheric thickening. Predictions from our model can fit well the observed data of heat flow, ocean floor topography and geoid off-sets along fracture zones, the last data base exhibiting the most sensitivity to thermal perturbations below the lithosphere. Our calculations show that the oceanic lithosphere is able to grow continuously up to $0\ (10^{9}\,\mathrm{yr})$, long past the flattening of the seafloor. We report here that the thickness of a thermally equilibrated lithosphere could reach about 250 km, which lies within the appropriate range of values for the continental lithosphere, as inferred from studies in seismology, flexure observations, and secular polar motions.

Finally we have proposed a new dynamical mechanism, operative only for a temperature- and pressure-dependent rheology. The idea is based on the formation of small-scale convective instabilities from an ascending flow passing through the low viscosity zone, which exists in virtue of the temperature- and pressure-dependent viscosity. Strong secondary convections results from a local increase of the mantle temperature by a couple of hundred degrees. The vertical velocity increases greatly and assumes a jet-like profile in a low viscosity channel with a minimum of $0(10^{16}\,\mathrm{Pa\ s})$. This secondary convection model can deliver the proper timescales for the uplift and thinning of the lithosphere, as observed geologically.

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SMALL-SCALE CONVECTION BENEATH THE TRANSVERSE RANGES, CALIFORNIA: IMPLICATIONS FOR INTERPRETATION OF GRAVITY ANOMALIES

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Tomographic inversion of upper mantle P wave velocity heterogeneities beneath southern California (Humphreys et al., 1984) shows two prominent features: an east-west trending curtain of high velocity material (up to 3% fast) in the upper 250 km beneath the Transverse Ranges and a region of low velocity material (up to 4% slow) in the 100 km beneath the Salton Trough. We interpret these seismic velocity anomalies as due to small-scale convection in the mantle. Using this hypothesis and assuming that temperature and density anomalies are linearly related to seismic velocity anomalies through standard coefficients of proportionality, leads to inferred variations of ~ ± 300° C and ~ ± 0.03 g/cm^3.

We use the "observed" density contrasts to construct a very simple 3-D model of flow and stress beneath southern California using an elastic lithosphere over a uniform viscosity half space. The model shows upwelling beneath the Salton Trough and downwelling beneath the Transverse Ranges, consistent with the seismically inferred density anomalies. Shear tractions of about 100 bars drive an overall NW-SE motion with convergence in the Transverse Ranges.

The gravity anomaly produced by the seismically-inferred density contrasts alone reaches + 50 mgal over the Transverse Ranges. The effects of surface downwarping due to density-driven mantle flow add an opposing gravity contribution that reduces this amplitude and can even reverse its sign, depending on the flexural rigidity of the lithosphere. A 20 km thick elastic lithosphere results in a gravity field with no net gravity anomaly along the axis of the Transverse Ranges, flanked by a low of about -30 mgal. This is generally consistent with the observed isostatic gravity map.

Although the flow model is certainly oversimplified, it shows that sublithospheric loads (and the accompanying mantle response) have an important influence on short-wavelength gravity anomalies. They also demonstrate that gravity anomalies of the type to be measured by GRM can result from subcontinental small-scale convection.

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EVIDENCE FROM SATELLITE ALTIMETRY FOR SMALL-SCALE CONVECTION IN THE MANTLE

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Small-scale convection can be defined as that part of the mantle circulation in which upwellings and downwellings can occur beneath the lithosphere within the interiors of plates, in contrast to the large-scale flow associated with plate motions where upwellings and downwellings occur at ridges and trenches. The two scales of convection will interact so that the form of the small-scale convection will depend on how it arises within the large-scale flow. Observations based on GEOS-3 and SEASAT altimetry suggest that small-scale convection occurs in at least two different ways.

Filtered geoids and smoothed topography have been constructed for the world's oceans using GEOS-3 altimetry and digital bathymetry (Parsons et al., 1983; Watts et al., 1984). Residual depth and geoid anomalies were derived by removing the variations in geoid and depth that result from changes in the thermal structure of the plates. The resulting geoid and depth anomalies in the wavelength band 300-4000 km vary in a coherent way over large parts of the oceans. This coherent behaviour, the amplitude of the geoid (~10 m) and depth (~1 km) anomalies and their wavelength (2000-3000 km) can be simply explained as the result of convection beneath the lithosphere in a layer driven by heating from below.

The principal contributions to calculated geoid and depth anomalies for convection beneath an elastic conducting lid come from horizontal temperature variations occurring just beneath the bottom of the lid. This is reflected in the effective depth of compensation determined from the geoid-depth relationship. An effective depth of compensation smaller than the thermally-defined plate thickness requires a viscosity structure such that the bottom part of the thermally-defined plate can also form the upper thermal boundary layer of the small-scale convection. This then allows the short timescales associated with the uplift of mid-ocean swells like Hawaii, the appropriate time-scale being that of advection across the upper thermal boundary layer.

A second, different form of small-scale convection is suggested by the lineated pattern of short-wavelength (200-500 km) undulations

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observed in SEASAT-derived data in the central Pacific Ocean (Haxby and Weissel, 1983). The lineated pattern can be seen clearly in SEASAT altimetry on descending arcs that has been bandpassed for wavelengths in the range 40-500 km or in the deflection of vertical along the same arcs smoothed to remove wavelengths shorter than 90 km. The pattern shows a number of distinct features. It is aligned with the direction of "absolute" motion of the Pacific plate. The pattern occurs over ocean floor that varies in age from 5 Ma to 65 Ma and is oblique to the fracture zones over pre-Miocene seafloor. The deflection of the vertical derived along arcs near the East Pacific is quiet in the 200-500 km wavelength range compared to arcs over ocean floor older than 5 Ma.

The lineated pattern can be interpreted as an expression of small-scale instabilities beneath the lithosphere that result from the cooling of the plate as it moves away from the ridge (Parsons and McKenzie, 1978). If the instability is to develop by ages as young as 5 Ma a low viscosity zone approximately 100 km thick beneath the plate with a viscosity lower by three orders of magnitude than the values obtained from studies of post-glacial uplift is required. The alignment of the instabilities with the direction of motion of the plate would then be a result of the shear flow that would be concentrated within this low viscosity zone.

The availability of GRM-derived gravity would enable the possibility of small-scale convection beneath stable continental regions to be investigated, e.g., in the area around the intra-plate volcanism in North Africa. Also a uniform gravity data set extending across continent-ocean boundaries would facilitate the analysis of gravity regardless of whether continental or oceanic tectonics was the primary concern.

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MANTLE VISCOSITY, $\dot{J}_2$, AND THE NONTIDAL ACCELERATION OF EARTH ROTATION

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Recent interpretations of laser ranging data for the LAGEOS satellite have rather conclusively established that the observed acceleration in the node of its orbit is just that expected to exist as a residual effect of the last deglaciation event which ended about 6000 years ago. The nontidal acceleration of rotation would be rather different than that observed if there were any significant melting of high latitude continental ice masses currently ongoing. The sensitivity of the expected nontidal acceleration to variations of several elements of the radial viscoelastic structure of the planet is explored using a new normal mode method for the computation of viscoelastic relaxation spectra. These calculations establish that the most important sensitivity is to variations in the mantle viscosity profile. Although the predicted nontidal acceleration does depend upon lithospheric thickness and on the elastic component of the radial structure, the dependence on these components of the structure is much weaker than it is upon mantle viscosity. The observed J_2 is therefore a particularly useful determinant of radial variations in the latter parameter.

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MODELING GRAVITY AND MAGNETIC FIELDS FOR CRUSTAL AND UPPER MANTLE STRUCTURES

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The purpose of this paper is to: (1) make a direct comparison between the gravity and magnetic fields near the ellipsoid and at the height expected for the Geopotential Research Mission (GRM) for the same geologic model, (2) obtain realistic estimates of the gradients that can be expected at the orbit height of the GRM, and (3) demonstrate the value of data that the GRM could provide for investigating upper mantle and deep crustal anomalies.

The fields that have been computed are the vector components of the gravity and magnetic fields, the components of the gradient tensors, and the components of the "second derivative" tensors of rank 3. The forward calculations were carried out for the same geologic model at heights of 2 and 160 km above the ellipsoid. A grid spacing of 50 km was used for the low-gradient portions of the 2-km-height field, and spacings of 25 and 5 km were used for the higher gradient portions of this field. A constant grid spacing of 100 km was used for the 160-km-height field. All components of the fields are given with respect to the north, east, and vertical directions.

The model is of a hypothetical rift valley. There is an elongate (approximately 1,300 by 240 km) region in the upper mantle where the density is lower than normal. This low-density region is 25 km thick at the axis and decreases in thickness linearly toward the edges. In the upper crust, the model includes a graben-type structure (about 450 by 80 km), with sides sloping at 45 degrees, that is filled with low-density material to depths reaching 5 km below the ellipsoid. The rocks along the sides of the graben are assumed to have magnetic properties, and the direction of the Earth's magnetic field is assumed to differ over various parts of the model. A crude topography has been included along the edges of the graben to represent mountain ranges. The susceptibility of the mountains varies from 0 to 8 A/m. The 8 A/m portion of the model represents a thick (up to 1.5 km) volcanic field on the northwest side of the graben. Additional sedimentary material has been included between the mountains so that the part of the graben above the ellipsoid is half full of low-density material.

The method of forward calculations is to construct the model from a set of bodies. Each body is completely bounded by plane polygons that can be in any orientation and can have an arbitrary number of vertices. Each body can have a density value, a susceptibility, or both. Each field is then computed using surface integrals over these bodies.

The long-wavelength gravity anomaly at 160 km orbit height would be clearly defined by the GRM. The vertical component would suggest an extensive low-density structure with added mass near its center. The gravity gradients place constraints on the length of the added mass of the topography, but do not resolve the width. Use of the combined GRM and near-surface gravity fields would place constraints on interpretive models that could improve the reliability of the solutions.

Gravity gradients with an accuracy of ± 0.01 Eötvös units appear to be adequate to define the gradient fields for this model at the GRM orbit height. The shorter wavelength content of the gradient components could be an important aid for delineating the trend and some dimensions of the structures that cause the gravity anomaly.

The magnetic field produced by the structures in this model is a combination of the lack of magnetic materials in the graben and induced magnetization in the flanking mountain ranges. The cumulative effect is a low-amplitude (- 3 nT), generally featureless anomaly that would be on the borderline of detectability by magnetometers of the type used on Magsat. This anomaly would be difficult to interpret without the gravity field over the same region. Correlation with the gravity field would indicate that the magnetically disturbed rocks are in a broad region of mass deficiency and correspond in location to the position of added mass in the low-density region. This would be an important guide for selecting the type of model to represent the anomalous features. An additional use of the combined fields would be to compute the pseudo-gravity field to obtain an estimate of the relative amounts of material that are disturbed due to density variations and due to susceptibility variations.

The magnetic gradients at this orbit height are small. A sensitivity of ± 0.001 nT/km would be needed to define the gradients with any degree of confidence. A lower measurement height, between 130 and 140 km, would significantly improve the quality of both the magnetic field and magnetic gradient measurements.

The example discussed in this paper is only one model. It would be desirable to carry out similar calculations for a variety of geologically realistic models to document the types of structures that the GRM may delineate.

VI. Oceanic Circulation

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N86-12881

ON THE GEOGRAPHICAL CORRELATION OF ORBIT ERROR

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The orbit accuracies needed to support the global crustal dynamics project and recent satellite altimeter missions have placed unique demands on the data analysis and orbit analysis systems. These demands include accurate and well-distributed observations, improved computational techniques and substantial enhancements in the force models which represent the satellite's motion. For example, the satellite altimeter mission (TOPEX), whose objectives will be 1) to measure the time variable ocean surface topography, and 2) to demonstrate the ability to map the general ocean circulation, requires that the radial component of the satellite's orbit be known with an rms accuracy of 13 cm for the three-year mission lifetime. The primary force model uncertainty which limits the contemporary orbit computation accuracy is the inaccuracy in the values assigned to the spherical harmonic coefficients used to model the earth's gravity field.

This presentation describes the effects of gravity model errors on previous satellite altimeter missions, looks at the projected effects of errors in the current geopotential model on the TOPEX Mission and describes the pre-mission studies which must be conducted to achieve the objectives of the TOPEX Mission. The investigations demonstrate that the radial orbit error, represented in a geographic sense, will contain a regionally dependent mean and variability and that it is not possible to use conventional ground-based tracking to remove these effects. The magnitude of the effects can be reduced by improvement in the knowledge of the gravity field. The conclusion reached in this investigation is that an order of magnitude improvement in the accuracy of the earth's gravity field models is required to realize the full potential of the TOPEX altimeter mreasurements.

N86-12882

GLOBAL MEAN SEA SURFACE COMPUTATION BASED UPON A COMBINATION OF SEASAT AND GEOS-3 SATELLITE ALTIMETER DATA

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A mean sea surface map has been computed for the global ocean areas between 70°N latitude and 62°S latitude based upon the 70-day Seasat and 3.5 year Geos-3 altimeter data sets. The mean sea surface is presented in the form of a global contour map and a 0.25° x 0.25° grid. A combination of regional adjustments based upon crossover techniques and the subsequent adjustment of the regional solutions into a global reference system has been employed in order to minimize the effects of radial orbit error. A global map of the crossover residuals after the crossover adjustments have been made is in good agreement with earlier mesoscale variability contour maps based upon the last month of Seasat collinear data. This high level of agreement provides good evidence that relative orbit error has been removed to the decimeter level on a regional basis. This represents a significant improvement over our previous maps which contained patterns, particularly in the central Pacific, which were due to radial orbit error. Long wavelength, basin scale errors are still present with a sub-meter amplitude due to errors in the PGS-S4 gravity model. Such errors can only be removed through the improvement of the earth gravity model and associated geodetic parameters.

Image processing techniques have been applied as a means of enhancing the detailed topographic structure contained in the map. Ocean surface expressions, ranging in amplitude from several meters to a few decimeters, of bathymetric features such as the Mid-Atlantic Ridge, the Mendocino, Murray and other fracture zones in the Eastern Pacific, deep ocean trenches, sea mounts and many other bathymetric features are clearly depicted. Significant improvement in the definition of the small amplitude short wavelength features (e.g., sea mounts, trenches, and fracture zones) has been achieved in this new map as a result of: 1) the increased resolution provided by the combination of the total Geos-3 and Seasat data sets, and 2) the reduction of the regional orbit errors.

Basin scale ocean circulation patterns computed by analyzing the difference between the mean sea surface map and the most accurate satellite derived long wavelength geoid are in good agreement with dynamic topography maps based upon hydrographic data.

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CONTRIBUTIONS OF GRM TO THE OCEAN TOPOGRAPHY EXPERIMENT (TOPEX)

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The permanent shape of the sea surface, the time-averaged mean sea level, is comprised of: (a) an ellipsoidal component due to the mean mass of a rotating earth; (b) spatial undulations due to the inhomogeneous distributiion of mass in the earth; and (c) spatial undulations due to permanent ocean currents. The amplitude of the three components are in the ratio 10^4: 10^2: 1 m, the first two components comprising the marine geoid, and the third being the permanent topography of the sea surface.

The TOPEX satellite is designated to map on a global grid the mean sea level averaged over a three to five year period with an accuracy of a few centimeters, using a radar altimeter in an accurately determined orbit. An improved understanding of earth's gravity field, such as that expected from the Geopotential Research Mission, will contribute to the TOPEX mission by contributing to the calculation of an accurate orbit (ephemeris), and by improving the accuracy of the calculation of permanent currents.

An accurate ephemeris results from numerical integrations of the equation of motion for the satellite using knowledge of gravity, air drag, and radiation pressure, subject to the constraints imposed by Tranet and perhaps other tracking data from the satellite. Of the many sources of error in the calculation, gravity errors dominate. For example, the vertical component of the Topex ephemeris, which is expected to be known with an accuracy of around 13 cm, should have gravitational errors amounting to 10 cm.

Calculations of permanent currents from the TOPEX maps of mean sea level require a marine geoid having an accuracy of much less than 10 cm over wavelengths ranging from a few hundred kilometers to tens of thousands of kilometers. The shorter wavelengths yield the circulation around bathymetric features, and the longer wavelengths yield the gyre-scale flow around and between ocean basins. Of the two extremes of scale, the gyre scale and longer are perhaps the most important. The gyre-scale currents are not well known, they make a large contribution to the topography, and they involve important global processes. Hence, this places a high premium on the accuracy of the longer-wavelength components of the geoid.

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SEPARATION OF CORE AND CRUSTAL MAGNETIC FIELD SOURCES

L. Shure, R.L. Parker, R.A. Langel

Fluid motions in the electrically conducting core and magnetized crustal rocks are the two major sources of the magnetic field observed on or slightly above the Earth's surface. The exact separation of these two contributions is not possible without imnposing a priori assumptions about the internal source distribution. Nonetheless models like these have been developed for hundreds of years (Halley, 1692; Gauss, 1838). Gauss' method, least-squares analysis with a truncated spherical harmonic expansion, has been the method of choice for more than 100 years although he did not address separation of core and crustal sources, but rather internal versus external ones. Using some arbitrary criterion for appropriate truncation level, we now extrapolate downward core field models through the (approximately) insulating mantle. Unfortunately our view can change dramatically depending on the degree of truncation for describing core sources.

Core sources cannot be uniquely determined even if we have error-free data everywhere and know all we need about the crust. There is still an infinite collection of electric currents consistent with the observations. One way to by-pass this inherent ambiguity, both for such idealized data or more realistic measurements, is to ask for the model which is, in some well-defined sense, the most simple one. It might be smallest or perhaps most like some other model which we favor.

The harmonic spline technique for constructing some kinds of smoothest models has already been discussed (Shure, Parker and Backus, 1982; Parker and Shure, 1982). We present here a preliminary harmonic spline model for 1980 based on a 4180-data subset of quiet Magsat vector measurements and compare this model to GSFC 9/80, a model representative of many produced by more traditional methods using the Magsat data. The spline model represents the core sources and is chosen so that the rms radial magnetic field at the core surface is nearly minimized. Several criteria are used to compare these two models mentioned including power spectra at both the core and surface, the distribution of null-flux curves at the core-mantle boundary (places where the radial field is zero) and the flux through these patches. We find there are 9 patches for the spline model while there are 11 for GSFC 9/80 which also appear more contorted. Finally the patch fluxes for the spline model are smaller than for the equivalent regions for GSFC 9/80 in spite of both models fitting the data equally well. These null-flux curves and patch integrals are used for making inferences about convection in the core and it is therefore important to estimate them and their associated errors correctly.

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THE MAGNETIC FIELD AT THE CORE-MANTLE BOUNDARY

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Models of the geomagnetic field are, in general, produced from a least-squares fit of the coefficients in a truncated spherical harmonic expansion to the available data. Downward continuation of such models to the core-mantle boundary (CMB) is an unstable process: the results are found to be critically dependent on the choice of truncation level (Benton, 1982). Modern techniques allow this fundamental difficulty to be circumvented (Shure, et al., 1982, Gubbins, 1983).

The method of stochastic inversion is applied to modeling the geomagnetic field. Prior information is introduced by requiring that the spectrum of spherical harmonic coefficients to fall-off in a particular manner which is consistent with the Ohmic heating in the core having a finite lower bound. This results in models with finite errors in the radial field at the CMB. Curves of zero radial field can then be determined and integrals of the radial field over patches on the CMB bounded by these null-flux curves calculated. With the assumption of negligible magnetic diffusion in the core - the frozen-flux hypothesis - these integrals are time-invariant.

Results are shown below for the field at 1970 and 1980.

Several important results emerge from these models:

1) The magnetic field at the CMB is very much more complicated than previously supposed. The error estimate for the radial field is about 50 μT, so even the smallest features seen in the models are 'real'.

2) The models are consistent with the frozen-flux hypothesis. Previously, the validity of this hypothesis had been doubted even on a time-scale of just ten years, as the hypothesis seemed inconsistent with the decay of the dipole (Booker, 1969).

3) Some of the features seem to indicate the existence of magneto-hydrodynamic waves in the core. MHD waves have long been proposed as an explanation of the secular variation, but have not previously been observed.

The frozen-flux hypothesis can be incorporated into the inversion as an additional constraint. Because the position of the null-flux curves changes with time, the constraint is non-linear and so has to be satisfied iteratively. Great care has to be taken, however, to ensure the procedure is convergent.

With the assumption of frozen-flux it should be possible to calculate certain components of the fluid motion at the top of the core. However, the models suggest that significant changes are occurring in high order terms (out to, say, degree 11) for which the secular variation is hard to determine accurately.

More data of the quality of the MAGSAT mission will be necessary to determine the secular variation, or, possibly, data covering a much longer time-interval.

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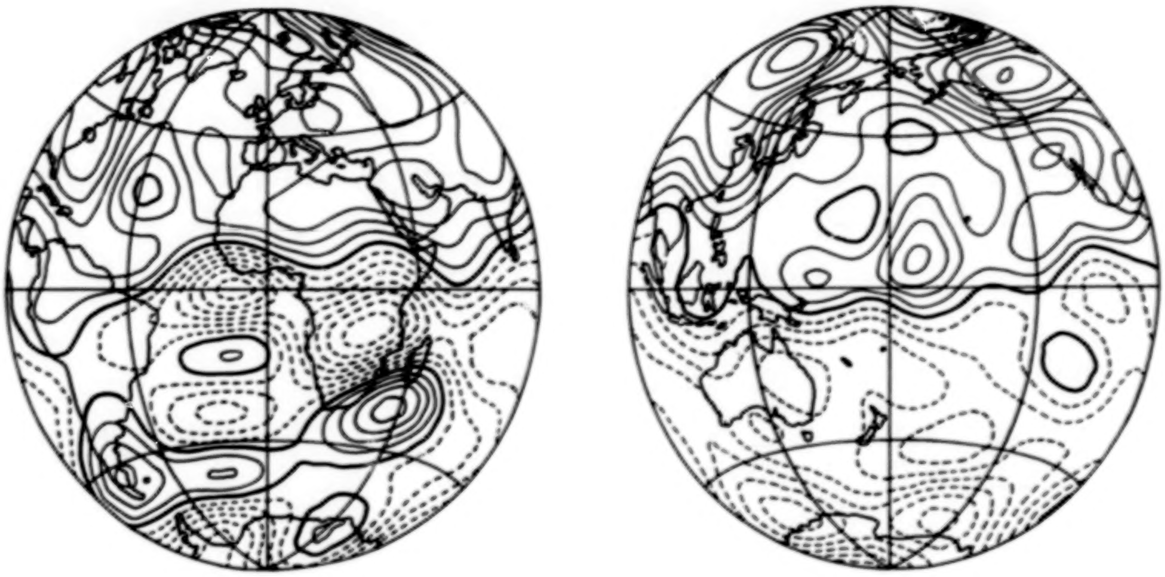
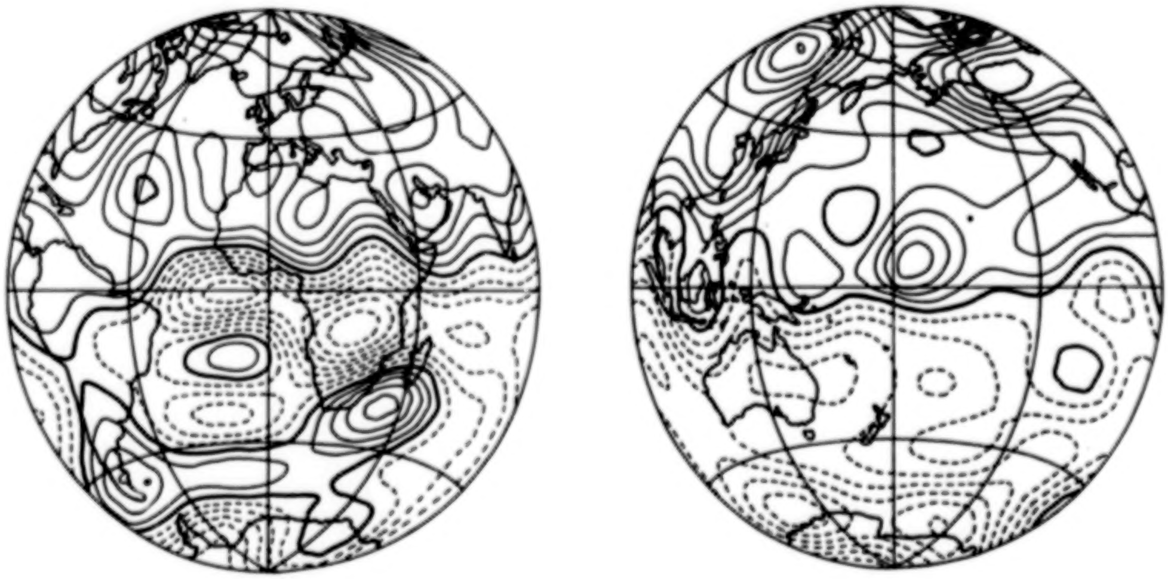
Contour maps of the radial field at the core-mantle boundary. The contour interval is 100 μT. The bold lines represent zero radial field, the continuous lines nagative radial field and the broken lines positive radial field.

1970



1980



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SOME ANTICIPATED CONTRIBUTIONS TO CORE FLUID DYNAMICS FROM THE GRM

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It is broadly maintained that the secular variation (SV) of the large scale geomagnetic field contains information on the fluid dynamics of earth's electrically conducting outer core. The electromagnetic theory appropriate to a simple earth model has recently been combined with reduced geomagnetic data in order to extract some of this information and ascertain its significance [Voorhies, 1984]. The simple earth model consists of a rigid, electrically insulating mantle surrounding a spherical, inviscid, and perfectly conducting liquid outer core. This model has been tested against seismology by using truncated spherical harmonic models of the observed geomagnetic field to locate earth's core-mantle boundary, CMB. Further electromagnetic theory has been developed and applied to the problem of estimating the horizontal fluid motion just beneath CMB. Of particular geophysical interest are the hypotheses that these motions (1) include appreciable surface divergence indicative of vertical motion at depth, and (2) are steady for time intervals of a decade or more. In addition to the extended testing of the basic earth model, the proposed GRM provides a unique opportunity to test these dynamical hypotheses.

Hide's [1978] method for magnetically determining the radius of earth's electrically conducting core rests on the following fact: if the core is, in effect, a perfect liquid conductor, then the number of field line footpoints at CMB must be conserved. The radius b^* of a spherical surface at which the absolute flux linkage,

$$\underline{P}(r,t) = \int_0^{2\pi} \int_0^{\pi} \| B_r(r,\theta,\phi;t) \| r^2 \sin\theta \, d\theta \, d\phi, \qquad (1)$$

is the constant, $\underline{P}(b^*)$, may thus be identified as the radius of the core. Here (r,θ,ϕ) are the geocentric spherical polar coordinates and B_r is the radial component of the magnetic flux density.

The assumption of an electrically insulating mantle of vacuum magnetic permeability allows the calculation of $B_r = -\partial V/\partial r$, hence $P(r,t)$, within the mantle by downwardly continuing a model of the scalar magnetic geopotential, $V(r,\theta,\phi;t)$. Conventional spherical harmonic representations of V should be truncated to degree and order $N_B \leq 12$ before downward continuation in order to reduce the effect of crustal magnetic anomalies on estimates of the core field [Langel and Estes, 1982]. The small scale structure of the core field thus lies concealed beneath the crustal field. Yet it is the behavior of the fairly well-known large scales of the core field, characterized by the first 100 or so time-varying Gauss coefficients, which we seek to explain and perhaps predict.

Terrestrial applications of Hide's method have been reported by Hide and Malin [1981], Voorhies and Benton [1982], and Voorhies [1984]. In the latter, the average of 44 magnetic determinations of the core radius is 3506 ± 301 km. Selection of an appropriate subset of field models yields the refined, inverse variance weighted mean value, $b^* = 3485 \pm 35$ km. Both values differ insignificantly from the seismically determined radius $b = 3485$ km. These results, along with those from a study of the global absolute and regional 'patchwise' flux linking CMB, demonstrate the validity of the source-free mantle - frozen-flux core approximation.

This approximation must nevertheless fail over sufficiently long time intervals or on sufficiently small spatial scales. Some evidence of flux diffusion has been found, but it is not yet compelling. This is primarily attributed to a currently inadequate temporal distribution of global vector magnetic data. The data acquired by the lead GRM spacecraft, when suitably reduced, would greatly help delineate the domain of validity of the basic earth model.

It has recently been shown that a steady fluid velocity at CMB, $\underline{v}(b,\theta,\phi) = (u = 0,v,w)$ is uniquely and globally determined by the time-varying radial component of the magnetic flux density, $B_r(b,\theta,\phi;t)$ [Voorhies, 1984; Voorhies and Backus, ms. in preparation). The testable assumption of steady motion thus resolves a fundamental ambiguity in finding $\underline{v}$ from B_r. To see this, note that the radial component of the pre-Maxwell magnetic induction equation evaluated at the top of an ideal liquid core,

$$\frac{\partial B_r}{\partial t} + \frac{v}{b}\frac{\partial B_r}{\partial \theta} + \frac{w}{b\sin\theta}\frac{\partial B_r}{\partial \phi} = B_r\frac{\partial u}{\partial r}\ , \qquad (2)$$

can be evaluated at three distinct epochs. This provides three distinct equations in the three steady unknowns $(\partial u/\partial r, v, w)$, hence unique solutions for $\underline{v}$ provided certain weak constraints are satisfied. If B_r is known, then (2) can be evaluated at an arbitrarily large number of epochs; the assumption of steady flow thus overdetermines the problem of finding $\underline{v}$ from B_r.

We therefore estimate that steady motion at the top of an ideal liquid core which best fits, in both the spatial and temporal least squares sense, a model of $B_r(b,\theta,\phi;t)$. To do so, set $\underline{v} = \nabla_s T \times r + \nabla_s U$, where T is the streamfunction and U the effective velocity potential, express T and U in terms of a truncated spherical harmonic expansion, and minimize

$$\int_{t_i}^{t_f}\int_{0}^{2\pi}\int_{0}^{\pi}\left[\frac{\partial B_r}{\partial t} + \frac{v}{b}\frac{\partial B_r}{\partial \theta} + \frac{w}{b\sin\theta}\frac{\partial B_r}{\partial \theta} - B_r\frac{\partial u}{\partial r}\right]^2 \sin\theta d\theta d\phi dt$$

with respect to the coefficients of T and U. Solutions [Voorhies, 1984] have typically been derived from the $N_B = 8$ GSFC 9/80 of Langel, et al., [1982] with the interval during which the motions are assumed to be steady, $t_f - t_i$, taken to be one or two decades. Such solutions are non-singular, relatively stable against changes in the number of T and U coefficients, and qualitatitively steady in that changes in t_i and t_f do not dramatically alter the derived motional pattern.

Steady, purely toroidal flows (U=0), suggested by Gubbins [1982], do not fit the input SV models at CMB as well as do steady, combined toroidal-poloidal flows - such as that depicted in Figure 1. This is particularly true when the steady motion hypothesis is relaxed by letting $t_f - t_i$ become small. The normalized root mean square SV residual at CMB, $\delta(\underline{v})$, which measures the difference between the input and 'predicted' SV, is typically 50% for purely toroidal flows and 30% for combined flows. Such results constitute relatively direct evidence of weak, large scale vertical motion near CMB.

The derived flows possess a bulk westward drift of about 0.107°/yr, but are complicated by superimposed jets, vorticies, and upwelling. Typical (rms) speeds and surface divergences are about 5.4×10^{-4} m/s and 2.3×10^{-10} s^{-1}, respectively. It has been found that the residual SV variance, $\delta(\underline{v})^2$, is nearly inversely proportional to both the number of T and U coefficients and to the interval $t_f - t_i$. Moreover, solutions for different intervals, although qualitatively similar, quantitatively differ enough to indicate unsteady flow. The motions are therefore not thought to be steady; however, the appreciable reductions in $\delta(\underline{v})$ obtained for combined flow by decreasing $t_f - t_i$ are not yet warranted by our knowledge of the large scale SV of the core field.

For the first 80 coefficients of the GSFC 9/80 in particular, the recommended 5 conditional standard deviation uncertainty estimates imply an nrms SV residual of less than 17% is unwarranted. Since these are considered minimum estimates of the total uncertainty in the large scale SV at CMB, the values of $\delta(\underline{v})$ obtained with $t_f - t_i = 10$ or 20 years (20% or 30%) are as small as are currently warranted. Thus, over decade intervals and Mm length scales, the reduced geomagnetic data is adequately described by the quasi-steady, large scale, combined toroidal-poloidal circulation of a frozen-flux core beneath an insulating mantle.

Given the basic earth model, the dawn-dusk uncertainties of the GSFC 12/83 [Langel and Estes, 1984] main field coefficients and the GSFC 9/80 SV coefficients have been used to estimate that nrms SV residuals of less than 13% at CMB would be warranted by a GRM-less-MAGSAT data based SV model. The data acquired by GRM should thus be capable of resolving whether or not the fluid motions at the top of the core are indeed time dependent.

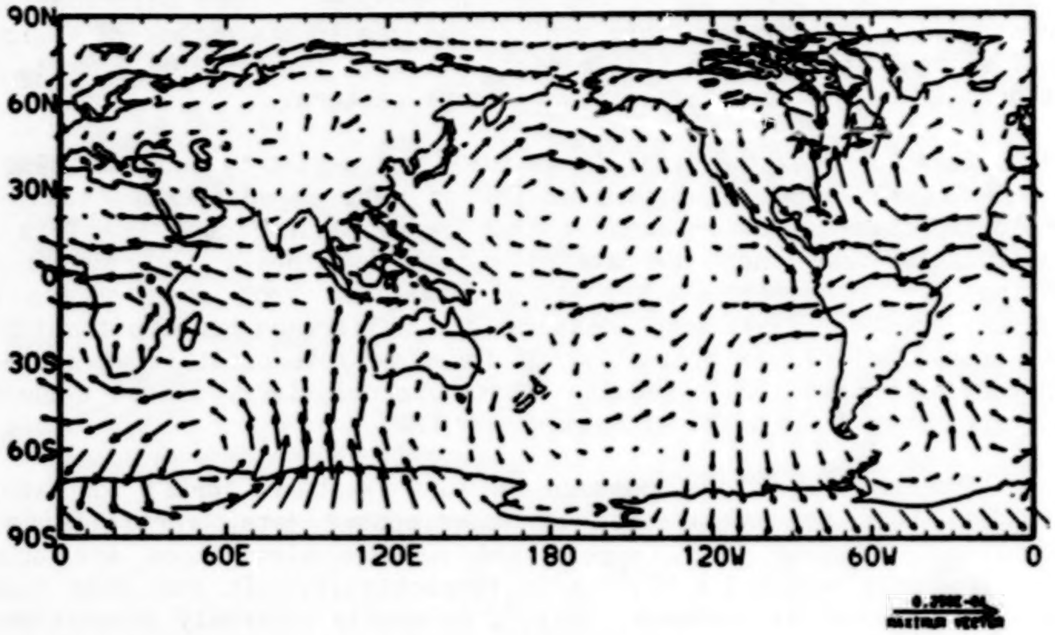

Figure 1. A steady combined flow at the top of Earth's core derived from the GSFC 9/80. Reference vector is 87.125 km/yr. $\underline{v}^{rms} = 16.44$ km/yr $= 5.21 \times 10^{-4}$ m/s.

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RATIONALE FOR A GRAVSAT-MAGSAT MISSION. A PERSPECTIVE ON THE PROBLEM OF EXTERNAL/INTERNAL TRANSIENT FIELD EFFECTS

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The earth's magnetic field at MAGSAT altitudes not only has contributions from the earth's core and static magnetization in the lithosphere, but also from external electric current systems in the ionosphere and magnetosphere, along with induced electric currents flowing in the conducting earth. Hermance (1982) has assessed these last two contributions; the external time-varying fields and their associated internal counter-parts which are electromagnetically induced.

It is readily recognized that during periods of magnetic disturbance, external currents often contribute from 10's to 100's of nanoteslas (gammas) to observations of the earth's field. Since static anomalies from lithospheric magnetization are of this same magnitude or less (Langel et al., 1980), these external source fields must be taken into account when attempting to delineate gross structural features in the crust. Hermance (1982) considered two questions: first, are, in fact, induction effects significant for near-earth satellite observations; second, what are the effects of lateral differences in the gross conductivity structure of the earth at satellite altitudes?

To assess global induction effects one can assume that, to the first-order, the earth is spherically symmetric and is illuminated by the magnetic field of an equivalent ring current system. Therefore, the source field, B_z^o, is assumed to be uniform and polarized perpendicular to the ecliptic plane over the earth's diameter. We adopt the usual spherical coordinate conventions such that in a geocentric coordinate system z is directed from the earth's center through the North Pole, θ is colatitude and r is the radial distance.

For the purpose of our present discussion we will approximate a region of high conductivity (the oceans at short periods, the upper mantle at longer periods) as a super-conductor ($\sigma = \infty$) at a radius of $r = a$.

One can derive the following ratios between the induced field components (B_r^i, B_θ^i) and the external source field B_z^o at the satellite altitude, r:

$$B_r^i/B_z^o = -(a/r)^3 \cos\theta, \qquad (1)$$

$$B^i_\theta/B^o_z = -0.5\,(a/r)^3 \sin\theta. \qquad (2)$$

It is clear that, for a satellite at a nominal altitude of 400 km one has an induced contribution of 34% - 42% (depending on the value of a) of the external field. Since, for example, during the recovery phase of a magnetic storm Dst may have magnitudes of 100 gammas or larger, one may have long-term induced fields which are several tens of gammas in magnitude; larger in fact at satellite altitudes than the static fields from most lithospheric magnetic anomalies (Langel et al., 1980).

There is little doubt therefore that significant induced fields persist at satellite altitudes. Recognizing the problematic aspect of this effect, one must also recognize that such an effect might be turned to one's advantage if a proper strategy can be devised to exploit phenomena associated with external/internal field coupling.

Hermance (1982) showed that, theoretically, such an approach is feasible and in fact argued that under suitable conditions one might be able to delineate the boundary between gross lithosphere structures which have rather subtle differences in electrical properties (an electrical contrast of only a factor of 2). It seems possible therefore that the investigation of the lithosphere in terms of its gross electrical properties might serve as a useful complement to studies of its large-scale magnetization properties.

In my view there have been some very strong arguments advanced in favor of a follow-on mission to MAGSAT. I can only endorse these statements. In addition I would add several arguments of my own in favor of such an experiment.

First, we extend the time base of our primary data set. By flying a second mission in several years we would acquire a better understanding of the long-term contribution from external fields (such as from the ring current) which may have time constants of months to years. In my mind we do not have an adquate time base to separate these external effects from internal secular variations or from long wavelength static anomalies in the lithosphere. Some of our recent work suggests that the MAGSAT reference field model may have as much as a 10 gamma residual due to external/internal field coupling.

Second, by flying this mission during all local times we have a unique opportunity to discriminate between the sources of the external field contribution, i.e., we can study both the effects of ionospheric current systems (during daylight hours, particularly during quiet magnetic conditions) and magnetospheric current systems. I cannot overstate the overwhelming advantages that satellites offer in terms of providing a synoptic view of these current systems. Ground-based observations of certain components of magnetic field variations (particularly the vertical field) are severely contaminated by the

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presence of induced currents in electrical heterogeneities such as the highly conducting oceans. We have been dramatically unsuccessful in reconstructing global patterns of induced current systems when relying on ground-based observatory data alone. The network is too sparce and one quickly encounters what is best described as aliasing effects in separating out local induction anomalies from larger scale regional anomalies. Satellite coverage provides a global view. And, at an altitude of 160 km, is far enough from truly local anomalies for the data to be unperturbed, while still close enough to the earth to potentially resolve regional anomalies (at the scale of 250 - 1000 km).

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RECENT MAGSAT RESULTS

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Meyer, et al., (1983) have improved their original global crustal model (Meyer, et al., 1984) and made a spherical harmonic analysis of the resulting magnetic field to n=50. Figure 1 shows the Z contours at 400 Km altitude from a field model composed of the first 15 degrees and order of their model and the terms n=16-29 from the Magsat model M051782 (Cain, et al., 1984). The main point to consider from such representations is that the lower order terms appear to contribute components comparable in magnitude to those of higher order. Thus one should allow in making tectonic interpretations of global maps of "anomalies" such as those published by Langel, et al., (1982), that there are likely continental scale (or smaller) features that have been removed along with the core field by the subtraction of the terms n=1 to 13 of the observed field. The view is also put forward by the paper by Hahn, et al., (1984). Planning for the analysis of data to be accrued by GRM should thus address this problem.

In the first determination of secular change from vector satellite data, Cain, et al., (1983) observed that the small quantity of observatory data available in 1981 for the Magsat analysis interval (September 1979 - June 1980) had little effect on the model M061581. Figure 2 is the secular variation from this model. Figure 3 is the same projection from the IGRF80 model (Peddie, 1983) which is very similar except for the north polar area. Cain, et al., (1983) concluded that the high rate of change in the northern regions was due to the increasing effect of the polar ionospheric currents as the Magsat orbit lowered and the current intensity increased as the seasons changed from northern winter to summer. Thus in order to obtain a model representative of the secular variation from the Earth's interior it would be necessary to model and eliminate the effects of these currents.

Pursuant to this elimination our group has collected and reduced, with the help of the World Data Center for Geomagnetism, the hourly values from some 60 magnetic observatories as depicted on Figure 4. The nighttime ($22-3^h$ local time), quiet (Kp,<2) values were then corrected for the Dst variation, the resultant points averaged for each day and a linear least squares fit made. This correction assumed that Dst represented the sum of the n=1 internal and external field at the magnetic equator and that the i/e ratio was 0.28. Likewise, the similar correction was made to the Magsat data as originally selected for the M061581 model (and also used for M051782). The corrected Magsat data were then combined with the new values of X, Y and Z for the 60 stations and an adjustment made to M051782 to degree and order 10 in both spatial and first time derivatives. In this instance, unlike in prior derivations, the observatory SV data were weighted ten times heavier than previously. These weights were originally taken as the standard errors of the linear fits (Schmitz and Cain, 1982). An attempt was made to increase the weights another factor of ten but the result was clearly suprious since many cells began to appear in the S.V. maps.

This new model, M070284, thus retains all M051782 terms from n=11 to 29, but improves somewhat on the secular terms (Fig. 5). The degradation of fit to the Magsat data was small, e.g., residuals of the Magsat scalar data increased from 12 to 15 nT. A comparison of this result is given in Figures 6, 7 and 8 for Bangui, Kakioka and Novosibirsk observatories comparing the IGRF80 with M070284. These plots are of the previously noted daily averages from each observatory (solid lines) along with the linear least-squares fit (dotted lines) and the model indicated (dashed lines). The adjustment required to plot the model values through the middle of each curve is given by the numbers to the right above each curve. This adjustment is mainly needed for the neglected very high order terms that result from local magnetic anomalies and, to a lesser extent, errors in the models. Generally, these adjustments agree with the observatory "biases" determined by Langel, et al., (1983). These plots illustrate that most of the M070284 computed secular variation matches the apparent SV for an observatory better than does IGRF80. However, it would appear that the high negative F remains for a part of the north polar area. Either there are not enough stations, the data are too noisy, or the observatories also reflect this high rate.

In lower latitudes the secular variation on Figure 5 generally agrees with that of the IGRF80 except where the latter does not follow the observatory trends. The increase of the secular variation degree and order to n=10 allowed more detail in the Asian region.

It is not obvious from the analysis to date whether the variations applied from the Dst corrected observatory data contain trends due to the external field. On a statistical basis one could determine the type of behavior that could be expected from quiet data from annual distortions of the magnetospheric topology (Campbell, 1984). Such average results may or may not apply to this specific year. Also, the Dst index used was determined only from four low latitude stations (Sugiura, private communication, 1984) and the levels subtracted in Figures 6-8 may contain some annual time. Figure 9 is a plot of the Dst values averaged for a whole UT data selecting only hours where Kp <2. It is surprising to find such large values even during such periods. The month-to-month changes in the H levels could be the result of the Dst correction applied. It is clear from such uncertainties that a definitive SV for the Magsat interval yet awaits a complete analysis of the external sources including their induced components.

In summary, it would appear that the use of a mix of observatory and GRM data even over less than a year intervals would allow an accurate determination of global secular variation. However, a more comprehensive analysis of the external currents would be required than is presented herein.

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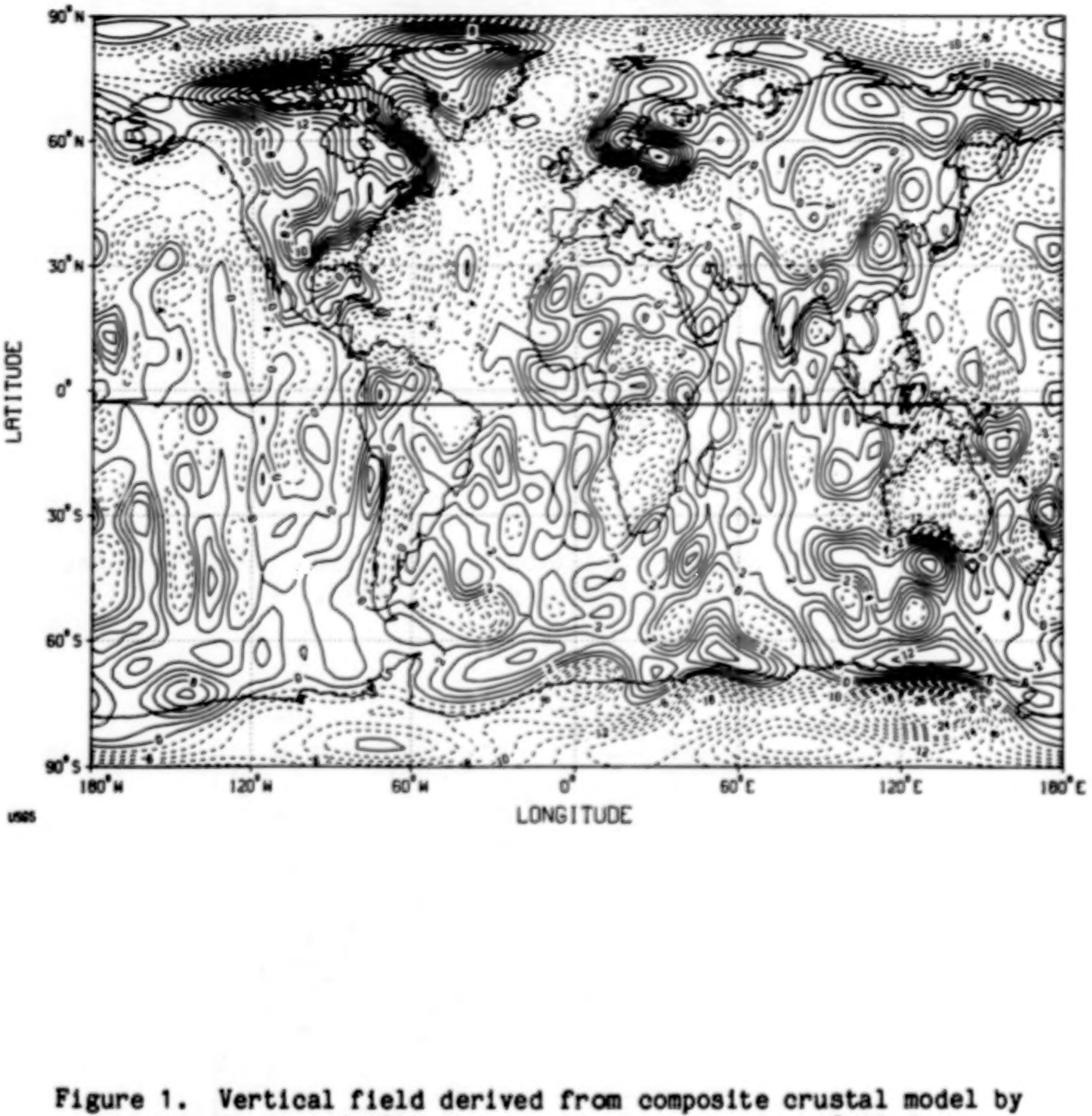
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Figure 1. Vertical field derived from composite crustal model by Meyer, et al., (1984) for n=1-15, plus terms n=16-29 from model by Cain, et al., (1983). Contours in nanoTesla at 400 Km altitude.

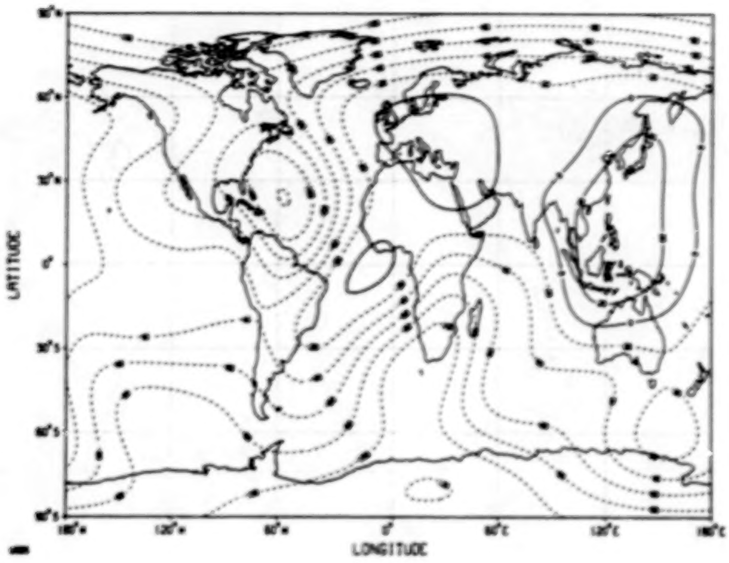
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Figure 2. 1980 secular variation in total field from the model M051782 (Cain, et al., 1983).

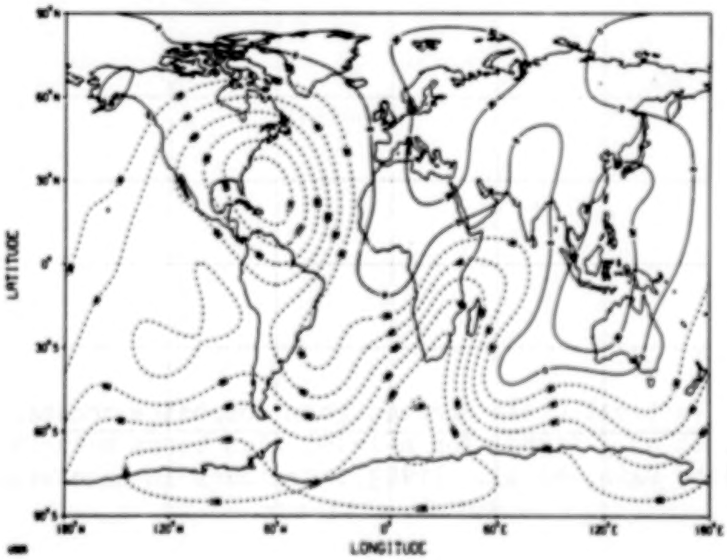
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Figure 3. 1980 secular variation in total field from the 1980 IGRF.

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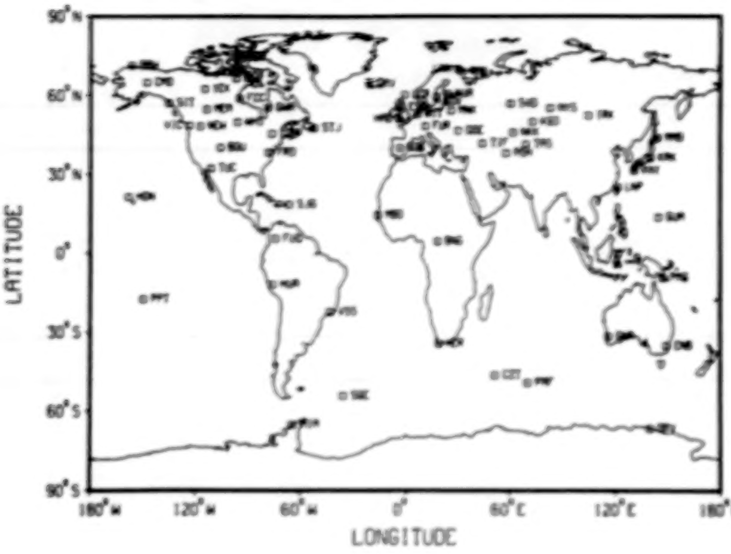
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Figure 4. Magnetic observatories providing hourly values during the Magsat analysis interval, September 1979 - June 1980.

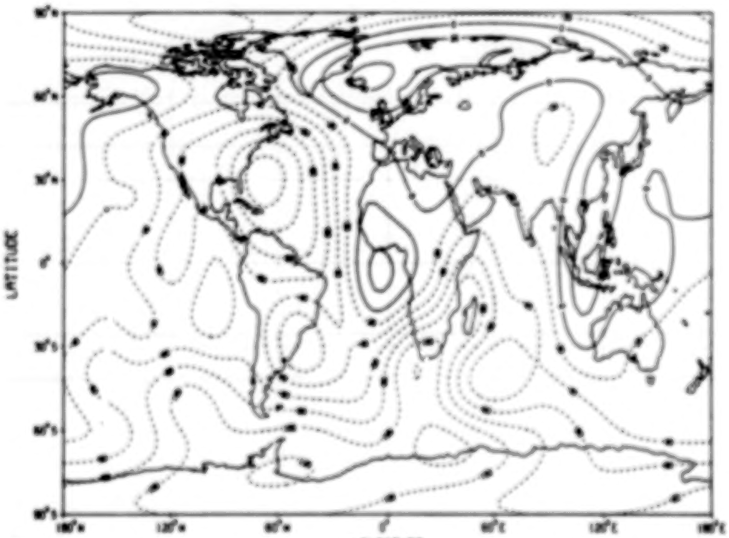
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Figure 5. 1980 secular variation in total field from the model M070284.

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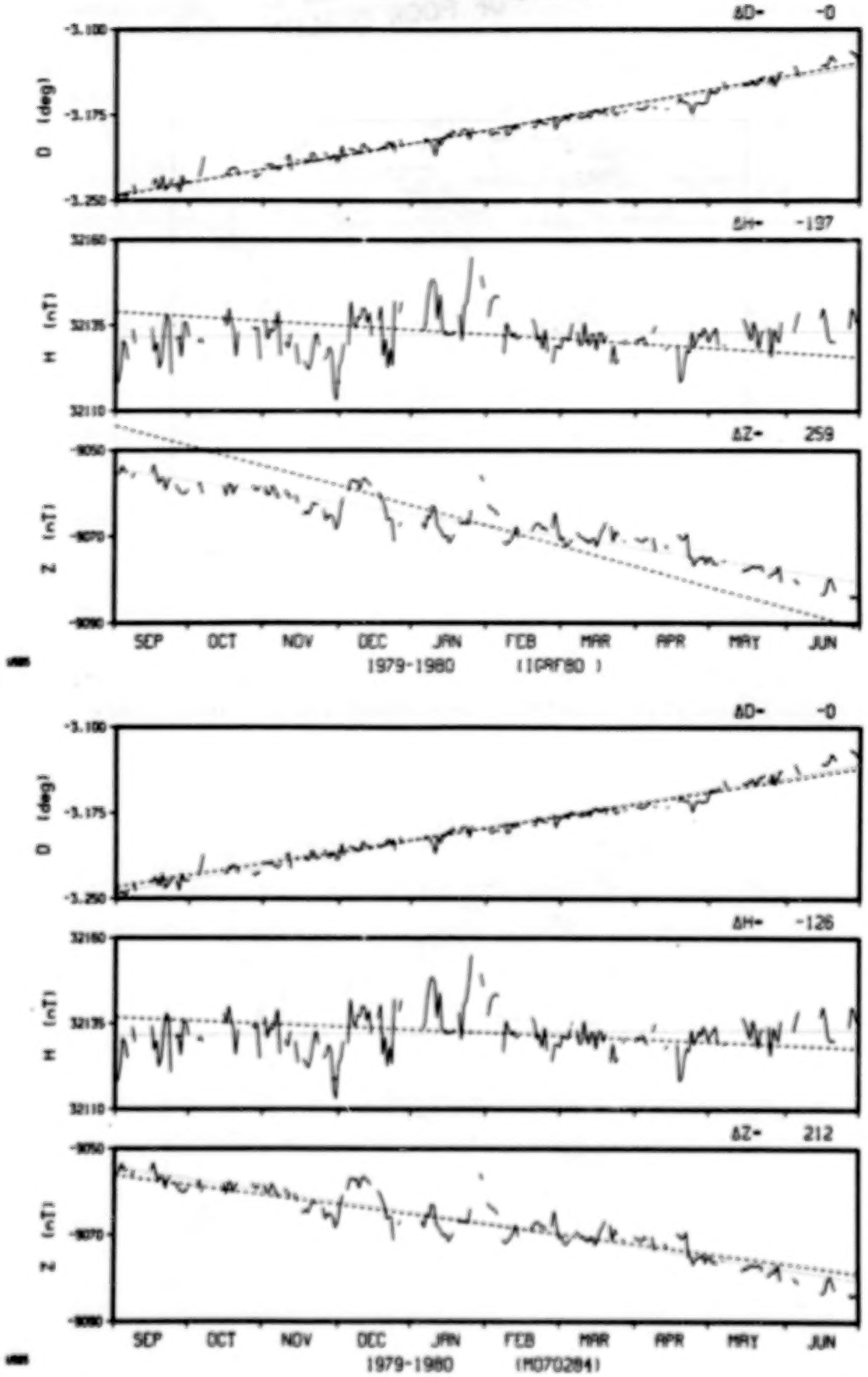
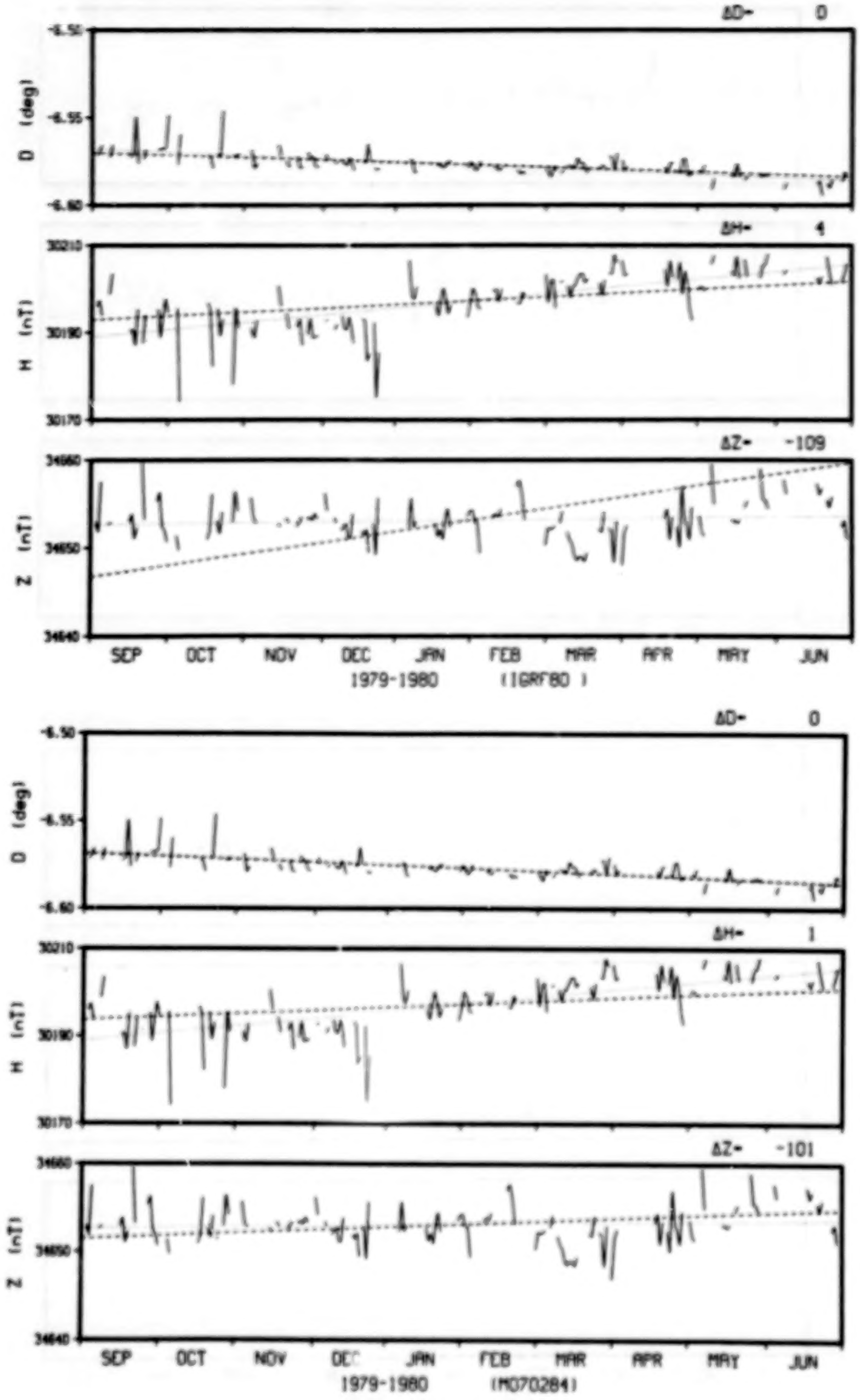


Figures 6a-6b. Bangui quiet, nighttime, daily means (solid lines) best fit (dotted lines), and model value (dashed lines) adjusted by values over each plot. $\Lambda = 5^{\circ}$.



Figures 7a-7b. Kakioka quiet, nighttime, daily means (solid lines), best fit (dotted line) and model value (dashed lines) adjusted by values over each plot. Λ = 26°.

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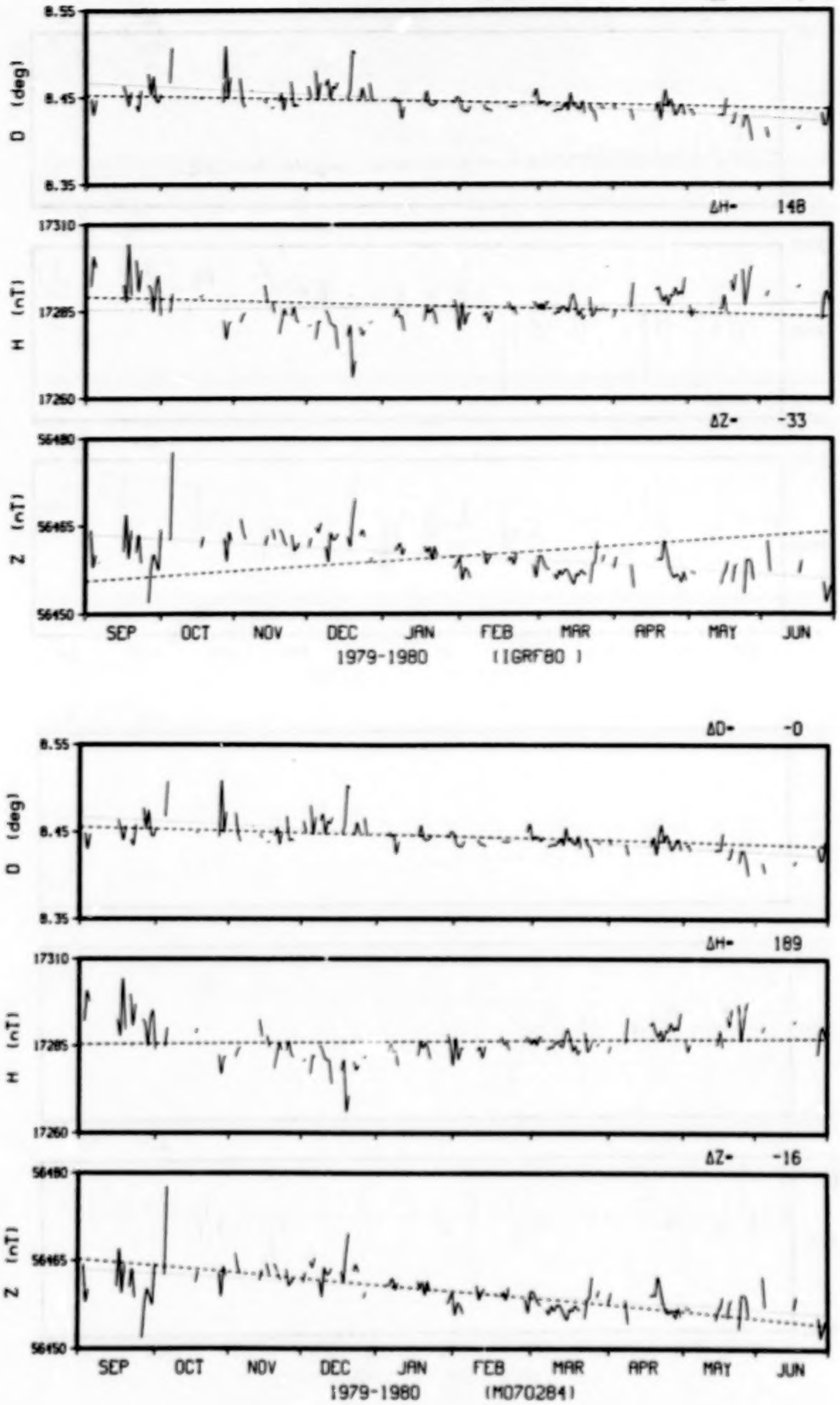

Figures 8a-8b. Novosibirsk quiet, nighttime, daily means (solid lines), best fit (dotted lines), and model value (dashed lines) adjusted by values over each plot. $\Lambda = 44^{\circ}$.

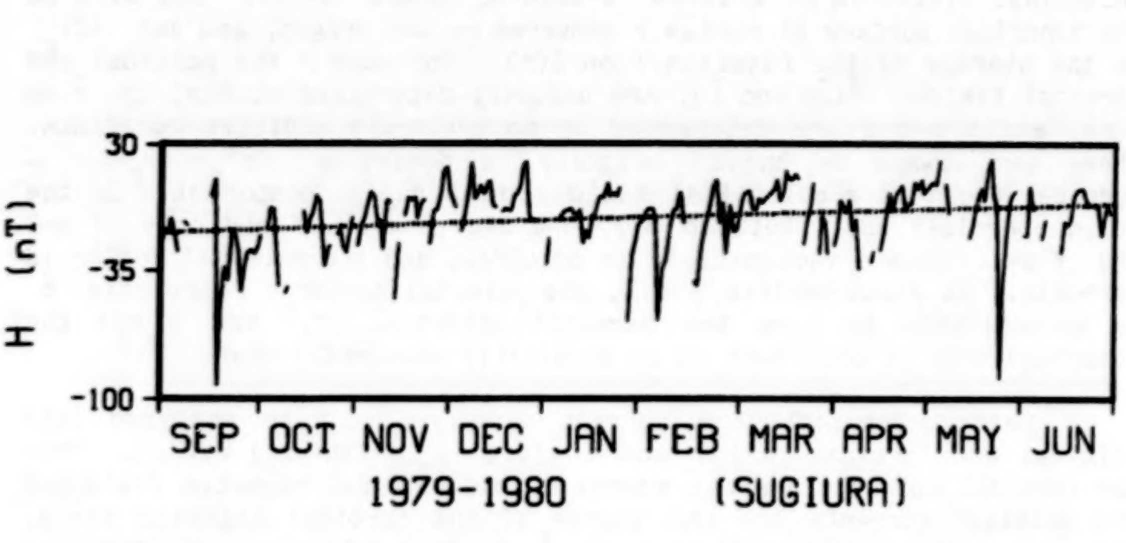

Figure 9. Average value of Dst for U.T. intervals for which $K_p<2$ using the data from M. Sugiura.

N86-12889

MODELING CURRENTS AT SATELLITE ALTITUDES

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In a conducting medium, the magnetic field cannot be written $\vec{B}=-\vec{\nabla}\psi$ because $\mu_0\vec{J}=\vec{\nabla}\times\vec{B}\neq\vec{0}$. However, $\vec{B}$ is still solenoidal, and any solenoidal field can be written $\vec{B}=\vec{\nabla}\times\vec{\Lambda}p+\vec{\Lambda}q$ where $\vec{\Lambda}=\vec{r}\times\vec{\nabla}$. Let S(r) be the spherical surface of radius r centered on the origin, and let $\langle f\rangle_r$ be the average of the function f on S(r). For each r the poloidal and toroidal fields, $\vec{\nabla}\times\vec{\Lambda}p$ and $\vec{\Lambda}q$, are uniquely determined on S(r) by $\vec{B}$ on S(r), and p and q are determined up to arbitrary additive constants. These can always be chosen uniquely by demanding $\langle p\rangle_r=\langle q\rangle_r=0$. A toroidal field is a solenoidal field without radial component. In the solid spherical shell between S(a) and S(b), $\vec{J}=\vec{0}$ if and only if $q=0$ and $\nabla^2p=0$. Thus a vacuum field is poloidal, and its poloidal scalar is harmonic. In a source-free shell, the poloidal scalar p represents $\vec{B}$ as economically as does the magnetic potential ψ; and p has the advantage that it continues to be physically meaningful where $\vec{J}\neq\vec{0}$.

Being solenoidal, the current density $\vec{J}$ can be analyzed into poloidal and toroidal parts, and in fact $\mu_0\vec{J}=\vec{\nabla}\times\vec{B}=\vec{\nabla}\times\vec{\Lambda}q-\vec{\nabla}(\nabla^2p)$. Thus the toroidal currents are the source of the poloidal magnetic field and the poloidal currents are the source of the toroidal magnetic field. For each r, the radial component of $\vec{J}$ on S(r) determines the toroidal part of $\vec{B}$ on S(r). If $\vec{B}$ is known on S(r) when J_r is determined there, as are the poloidal magnetic fields produced by the toroidal currents inside S(r) and by those outside S(r). The sources of the poloidal magnetic field on S(r) are inside and outside S(r), while the sources of the toroidal magnetic field on S(r) are on S(r) itself. If $\vec{B}$ is known on S(a) and S(b) then the radial averages in $a<r<b$ of the toroidal current and the tangential component of the poloidal current can be determined.

Analysis of p and q into surface spherical harmonics can replace the conventional Gaussian analysis of the vacuum field. However, the radial dependence of the spherical harmonic coefficients for p and q is arbitrary in current-carrying regions unless some further physical hypothesis is introduced. At MAGSAT altitudes, a reasonable hypothesis is $\vec{J}\times\vec{B}=\vec{0}$ (field-aligned currents, or a force-free plasma). This hypothesis greatly reduces the space of field-models to be considered, and at MAGSAT altitudes it can be implemented by linear iteration with a vacuum field as the first step. One must recognize, however, that even with $\vec{J}\times\vec{B}=\vec{0}$ the magnetic effects of $\vec{J}$ are non-local. Polar currents produce equatorial magnetic fields.

N86-12890

EXPECTED CONTRIBUTION OF THE GEOPOTENTIAL RESEARCH MISSION (GRM) TO STUDIES OF LIQUID CORE FLUID DYNAMICS

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A number of significant questions in geophysics ultimately require magnetic data before progress can be expected: (1) what is the instantaneous configuration and temporal evolution of the magnetic field in the near region external to the Earth? (2) how is permanent and induced magnetization of the crust (above the Curie isotherm) distributed in detail and what is its relationship to surface geology? (3) how large is the electrical conductivity of the deep mantle? (4) is electromagnetic core-mantle coupling strong enough to contribute significantly to observed changes in earth's rotation rate? (5) how does the main magnetic field emanating from the liquid outer core change in time, both in the short run (on time scales of years to decades) and in the longer term (over centuries to millenia and beyond)? (6) what is the source of mechanical energy and the pattern of resulting fluid motion that continually operates as a homogeneous, self-excited dynamo in the outer core? Is the toroidal field in the core weak (~10 gauss) or strong (~100 gauss or more)? (7) what is the heat flux delivered to the core-mantle boundary by fluid motions at depth and does its pattern contribute both to deep mantle plumes and to driving of surface plate tectonics? (8) can the large scale main magnetic field at earth's surface be at all well forecast over a 5 to 10 year period?

GRM can be anticipated to contribute strongly to some items on this list, moderately to others, and hardly at all to the rest. For example, hopefully, one major geomagnetic contribution will be a definitive resultion (at about 100 km) of the crustal magnetic anomaly pattern (item #2) in such a way that it can subsequently be removed from the observations to expose the remaining main magnetic field of deep internal origin. This spatial resolution expected from GRM, enhanced compared to MAGSAT, is obtained primarily from the lower (160 km) orbit height. Yet, that same feature exacerbates the contamination of the observations by ionospheric currents because GRM will fly directly through them. Moreover, the concommitant short lifetime makes it doubtful that GRM can contribute significantly to the direct determination of either continuous geomagnetic secular variation or deep mantle conductivity. On the other hand, there are good prospects for significant contributions to studies of fluid dynamics of the top portions of the liquid outer core.

All fluid dynamic studies to date rest on the frozen flux model for core motions in the low frequency pre-Maxwell theory of electromagnetism. That theory has also survived, very well, a test against seismology. The fluid velocity $\vec{v}$ (relative to the rotating mantle) then interacts with the main magnetic field, $\vec{B}$, to produce secular variation, $\partial\vec{B}/\partial t$:

$$\frac{\partial\vec{B}}{\partial t} = \nabla x(\vec{v} x \vec{B}) \ . \qquad (1)$$

Measurements of $\vec{B}$ and $\partial\vec{B}/\partial t$, taken at and above earth's surface can then, in principle, be downward extrapolated through the mantle which is usually assumed to be an insulator, but which need not be (if only its conductivity structure were known). Then (1) can be inverted for $\vec{v}$ just beneath the core-mantle boundary. Two immediate difficulties are that $\vec{v}$ is a highly nonlinear functional of the observations and moreover, only the component of $\vec{v}$ orthogonal to $\vec{B}$ can be recovered at a single epoch (the details of this ambiguity were originally probed deeply by Backus in 1968).

Recently, Voorhies and Backus have discovered one way to resolve that ambiguity completely (by introducing another physical assumption, namely that the fluid velocity is steady in time). Voorhies' doctoral thesis implements the theory and finds the unique steady motion consistent with magnetic field models based on the interval for 1960 to 1980. Subdividing this period into two decades and then comparing the resulting flows provides a test of the steady motion assumption. The GRM magnetic data, hopefully, not much later than 1990, will increase the total useable data span by 50%, thereby providing a far more satisfactory test for this theory.

Also, equation (1) plus the simplified equations of fluid mechanics imply the existence of a number of physical constraints on both secular variation and core fluid motions. GRM data are needed for thorough testing of these constraints.

Finding satisfactory models of the fluid motions at the top of the core is important for delineating what kind of dynamo is in operation, for estimating the heat flux into the base of the mantle, and for forecasting the magnetic field forward in time. Each of these aspects will be discussed.

N86-12891

THE SOURCE OF THE INTERMEDIATE WAVELENGTH COMPONENT OF THE EARTH'S MAGNETIC FIELD

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The intermediate wavelength component of the Earth's magnetic field has been well documented by observations made by MAGSAT. It has been shown that some significant fraction of this component is likely to be caused within the core of the Earth. Evidence for this comes from analysis of the intermediate wavelength component revealed by spherical harmonics between degrees 14 and 23, in which it is shown that it is unlikely that all of this signal is crustal. Firstly, there is no difference between average continental source strength and average oceanic source strength, which is unlikely to be the case if the anomalies reside within the crust, taking into account the very different nature and thickness of continental and oceanic crust. Secondly, there is almost no latitudinal variation in the source strength, which is puzzling if the sources are within the crust and have been formed by present or past magnetic fields with a factor of two difference in intensity between the equator and the poles. If however most of the sources for this field reside within the core, then these observations are not very surprising.

It is believed that most of the core sources are subject to some form of secular variation. This means that after a period of time, the spherical harmonic coefficients which produce these changes should change. In contrast, sources produced by remanent or induced magnetization within the crust would not be expected to change in any significant way, except for the small decrease in source strength of induced sources as the dipole field of the Earth decays with time (this decay is at a rate of 0.082% per year). Recent compilations of the field have calculated secular variation (SV) of coefficients up to degree eight. Using SV and models of the field at previous epochs it is possible to show that the relative change of amplitude increases with the degree of the harmonic. For instance the degree three harmonics change at a rate of 0.53% per year. This relative change increases in a fairly regular manner until at degree eight the relative change is 3.8% per year. This suggests that at higher degrees of harmonic it should be possible to see changes in coefficients if they indeed are caused by sources within the core of the Earth. Various models have been produced of the Earth's magnetic field at epoch 1980.0, based mainly on MAGSAT data. A comparison between these models shows that in general there is a fairly high correlation between individual spherical harmonic coefficients. This means that, given another accurate measurement of the Earth's magnetic field provided by GRM or MFE, it should be possible to detect changes in the higher degree coefficients (greater than 14) if the sources for these fields do indeed reside within the core of the Earth.

The increase in the resolution provided by GRM will also be of considerable use. It will be easier to tie individual anomalies to crustal structures if indeed they are caused by crustal field sources. To given an idea of the increase in resolution, the RMS field for a typical sea floor spreading situation was calculated (spreading rate 50 km/my, reversal rate 2/my, magnetization 1.0 A/m, thickness 6 km). For a height of 400 km the RMS field was 0.58 nT, whereas for a height of 160 km the RMS field was 2.5 nT. More importantly, there is much more power at larger wavenumbers. The wavenumber band between 0.014 and 0.032 (wavelength between 200 and 450 km) contains an RMS signal of 1 nT. At this wavenumber band the data from MAGSAT do not have any correlatable signals. For a dipolar source within the crust, the RMS field at the satellite altitude increases by a factor of 4.0 if the satellite altitude changes from 400 km to 160 km.

N86-12892

DOES THE GEOID DRIFT WEST?

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In 1970 Hide and Malin (Nature 225, 605) noted a correlation of about 0.8 between the geoid and the geomagnetic potential at the earth's surface when the latter is rotated eastward in longitude by about 160 degrees and the spherical harmonic expansions of both functions are truncated at degree 4. From a century of magnetic observatory data, Hide and Malin inferred an average magnetic westward drift rate of about 0.27 degrees/year. They attributed the magnetic-gravitational correlation to a core event at about 1350 A.D. which impressed the mantle's gravity pattern at long wavelengths onto the core motion and the resulting magnetic field. The impressed pattern was then carried westward 160 degrees by the ensuing magnetic westward drift. An alternative possibility is some sort of steady physical coupling between the magnetic and gravitational fields (perhaps migration of Hide's bumps on the core-mantle interface). This model predicts that the geoid will drift west at the magnetic rate. On a rigid earth, the resulting changes in sea level would be easily observed, but they could be masked by adjustment of the mantle if it has a shell with viscosity considerably less than 10^{21} poise. However, steady westward drift of the geoid also predicts secular changes in g, the local acceleration of gravity, at land stations. These changes are now ruled out by recent independent high-accuracy absolute measurements of g made by several workers at various locations in the northern hemisphere.

N86-12893

GRM AS A FOLLOW-ON TO MAGSAT

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Magsat was the first near-earth spacecraft dedicated to measurement of the vector geomagnetic field. Its objectives were to use the vector measurements to measure and model both the main field and the crustal field of the earth. The main field measurements were to be used for the 1980 world charts and to study the earth's core. The crustal fields were to be utilized to aid in modeling large-scale variations in the geologic and geophysical characteristics of the crust.

Main field modeling efforts have been spectacularly successful, even beyond expectation. The near-earth field at 1980 is now extremely well-defined, including the long-wavelength external field contribution. Further, studies relating to the fluid core have been undertaken with some success, as will be reported in other papers.

A large amount of the effort expended on the crustal field measurements has been focused on an understanding of the data, rather than its interpretation. Questions addressed have been:

1. How much of the so-called crustal field is really crustal?
2. How much of the total crustal field is included and how much is masked by the main and external fields?
3. What is the true zero level of the crustal field, or, what is the effect of not knowing this zero level?
4. Why do the crustal fields seem to have an east-west elongation?
5. Do the vector measurements provide additional information beyond what is contained in the scalar anomalies?

Many of us are now convinced that our maps do indeed represent crustal fields, at least to within ±2 nT, and that the north-south anomaly gradients can be discussed with reasonable accuracy. It now seems clear that the very longest wavelength crustal fields are masked by the core field. Much of the ocean-continent difference is contained in these wavelengths. At the short wavelength end, the limitation is imposed by the fact that our average altitude is about 400 km and the measurements have a finite noise level. This limitation constitutes the resolution limit of the measurements and has been variously estimated to lie between 250 and 600 km. The east-west elongation is partly due to the field geometry but is also contributed to by the fact that the satellite path is nearly north-south and along-track filtering is required to eliminate external fields. The question of the value of vector data in anomaly studies has been answered in the negative by Mayhew but I believe the question is still open.

The full answer to the usefulness of the vector data requires theoretical study, not more data. A lower inclination orbit, preferably about 50°, is required to finally resolve the questions about the east-west trends. An undeterminant zero-level remains a consequence of the presence of the main field. GRM will not address any of these problems.

Some actual crustal modeling has been accomplished. This includes models of Broken Ridge, the Lord Howe Rise, and the Churchill-Superior boundary zone. It has now been shown that sea floor spreading anomalies have a signature in the satellite data and that, in some regions, it is possible to utilize the satellite data to aid in mapping the depth to the Curie isotherm.

In addition to the problems already mentioned, the major limitation for crustal studies lies in the lack of resolution. This would be addressed directly by GRM. Resolution is a very strong function of altitude, but is also strongly dependent upon the distance between the bodies when separation is less than the observational altitude. The increase in resolution due to decrease in altitude from Magsat (~350 km) to GRM (~150 km), for bodies separated by distances approximately equal to or greater than Magsat altitude (350 to 550 km) is about an order of magnitude. As the separation decreases below the altitude of Magsat, the increase in resolution dramatically increases (to a factor of ~30 for body separation of 250 km and to a factor of ~300 at 150 km body separation). At approximately GRM and lower altitudes, widely separated bodies (>250 km) are distinct--that is, bodies of different separation have approximately the same resolution at any given altitude. This situation simplifies interpretation, as differences in resolution can be attributed to differences in susceptibility or volume. At Magsat altitudes the same bodies separated by 250 to 550 km will have resolutions which vary by about an order of magnitude, complicating interpretation.

Although not explicitly designed to study the main field, nevertheless the GRM data should yield a main field model at its epoch of comparable quality to those derived from Magsat data. The combination of GRM, Magsat, and magnetic observatory data should yield an improved definition of secular variation and, therefore, enable more detailed study of processes in the core which generate the main field.

N86-12894

ON THE INTERPRETATION OF SATELLITE-DERIVED GRAVITY AND MAGNETIC DATA FOR STUDIES OF CRUSTAL GEOLOGY AND METALLOGENESIS

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Satellite-derived global gravity and magnetic maps have been shown to be useful in large-scale studies of the Earth's crust, despite the relative infancy of such studies. Numerous authors have made spatial associations of gravity or magnetic anomalies with geological provinces. Gravimetric interpretations are often made in terms of isostasy, regional variations of density, or of geodesy in general. Interpretations of satellite magnetic anomalies often base assumptions of overall crustal magnetism on concepts of the vertical and horizontal distribution of magnetic susceptibility, then make models of these assumed distributions. The opportunity of improving our satellite gravity and magnetic data through the proposed Geopotential Research Mission should considerably improve the scientific community's ability to analyze and interpret global magnetic and gravity data. As data processing techniques improve, we may expect to see even more useful results of the data.

The satellite magnetic anomaly maps produced to date contain a series of east-west bands upon which are superimposed anomalies of shorter wavelength that are interpretable in terms of known crustal geology. The east-west bands have been interpreted as being caused by (1) data reduction in the preparation of the gridded anomaly data set, (2) incomplete removal of signal from subcrustal sources, (3) magnetospheric "noise," or (4) a combination of these. Gaussian-Fourier band-pass filters can enhance the shorter wavelength anomalies resolvable by the satellite system while suppressing even shorter wavelength noise and longer wavelength banding. Such filtering is performed on a plane rather than on a curved earth, but the technique appears to be useful[1] for the relatively short wavelengths being enhanced.

The band-pass filtered Magsat scalar anomaly map shows anomalies that are more clearly correlated with geologic features than does the unfiltered map. For example, the North Atlantic Continental Rise and Shelf, Bermuda Rise, Mid-Atlantic Ridge, Madeira-Torre Rise and African Continental Rise contribute to a NNE trending series of parallel filtered Magsat anomaly highs in the North Atlantic Ocean, separated by parallel lows over the Blake-Bahama-Hatteras Abyssal Plains, Sohm-Narea Abyssal Plains, and Iberia-Maderia-Cape Verde Abyssal Plains. Although remanent magnetization is likely to be an important factor in these anomalies, there also appears to be a strong correlation between the sign of the anomalies and uplift or depression of the crust in the North Atlantic Ocean. These features are not clearly distinguishable from the east-west bands on the original unfiltered anomaly maps. Similar patterns are generally not clearly distinguishable in the Central and South Atlantic Oceans - perhaps because of the significantly weaker main field strength in these areas.

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[1] Keeping in mind that the filtering is in terms of degrees of latitude and longitude, not directly in terms of linear distance.

Partly because of the stronger residual anomaly pattern over continents than over oceans, satellite magnetics appear to be more useful in investigating possible vertical movement of blocks of continental crust than for oceanic crust. Magsat anomalies of the continental crust, especially band-pass filtered anomalies, tend to be defined by large-scale crustal features such as Archaean shields and (to a lesser degree) lower Proterozoic shields, basins, and rift systems. They are less responsive to individual mountain ranges within a mountain block such as the Himalayas, and to individual grabens within a rift system. This is probably partly a factor of scale (the latter features are too small to be clearly resolvable), and partly because of greater overall differences in magnetic susceptibility in crustal blocks defined by surface representations of major tectonic units than by surface representations of smaller structural features.

The Magsat anomaly response of Archaean shields tends to be characteristic of relatively high average magnetic susceptibility, consistent with a combination of higher upper crustal susceptibility (higher metamorphic grade, more mafic average composition, more igneous rocks, or simply more low-grade magnetite mineralization), and/or the existence of a greater amount of relatively highly susceptible lower crustal materials uplifted above the Curie isotherm. This is true, to a lesser extent, for lower Proterozoic shields. The deepest parts of basins, corresponding to the thickest cover of relatively nonmagnetic sedimentary rocks over a depressed crustal column (with relatively less susceptible materials at every depth relative to the Archaean shield) are generally marked by anomalies characteristic of low relative susceptibility.

The anomaly pattern in the North Atlantic is an example of the band-pass filters enhancement of relatively short wavelength features that, in retrospect, are visible but not clearly distinguishable in the original unfiltered anomaly maps. These and similar features on the continents may have fundamental significance to our understanding of global tectonics and the formation of mineral and hydrocarbon deposits.

One example is the Pisco-Jurua Fault of Szatmari (1983). This fault extends between Pisco on the southern Pervian coast, along the trend of the Jurua River, to northern Guyana, and is marked by shear zones and intrusives of Jurassic age. In a reconstruction of Pangaea, this trend aligns with the axis of the North Atlantic Rift. Szatmari (op. cit.) has suggested that the Pisco-Jurua fault formed the southwestern continuation of the North Atlantic Rift. As the North Atlantic opened, according to Szatmari, northwestern South America moved relatively southwestward along the Pisco-Jurua Fault creating several major tectonic features along this trend: the Takutu Graben in the Guyana Shield, the gently folded Jurua Zone in the middle Amazon Basin, and the Pisco-Abancay deflection of the Cordillera. A band-pass filtered Magsat scalar anomaly low follows the trend the Pisco-Jurua Fault. At near-equatorial latitudes, this signifies a band of relatively high susceptibility consistent with uplift, intrusion of mafic materials, and/or relatively high metamorphic grade. This analysis and Szatmari's hypothesis can be combined to suggest that the Pisco-Jurua Fault line and the axis of the North Atlantic Rift were the axis of a pattern of convectional upwelling in the early Mesozoic. The pattern caused break-up of North America from Europe, but apparently did not develop so far in South America. If this hypothesis is true, the flanks of this anomaly pattern may mark likely locations for the emplacement of kimberlites and carbonatites (in appropriate structural settings) and other forms of mineralization associated with convectional upwelling.

A second example lies along the trend of the Middle America Trench on the Pacific margin of Central America. The trench is characterized by Magsat anomaly highs, with Central America itself being marked by low latitude Magsat lows that blend into the mid-latitude lows of the western Caribbean Basin. The trend of Magsat highs can be followed southeasterly from the Middle America Trench across South America to the Santos Basin. The lows can be followed across South America to the Rio Grande Rise off the Brazilian coast. Whereas the highs mark the Middle America trench along the continent-ocean transition along Central America, they follow a trend of sedimentary basins in South America. Similarly, the lows follow a trend of Precambrian uplifts, plus the Rio Grande Rise. The general lack of deep focus earthquakes along the Andes Cordillera and the various views of the subduction process along the Pacific margin of Central America suggests that this process may not fit the classic model of subduction. That one of the two South American zones of deep-focus earthquakes lies under the Acre (western Amazon) Basin, along the aforementioned trend of Magsat highs, supports the suggestion that this trend may mark a trend of convectional downwelling. At the continental margin of Central America this downwelling is associated with a "classic" Benioff zone. Under South America, the less dense, more rigid continental crust responds to the downwelling with broad, subdued depressions (sedimentary basins) in place of trenching, with the continental crust providing boundary conditions that result in subduction and the formation of the Cordillera along the Pacific coast. A parallel trend of uplifts extends between Central America and the Rio Grande Rise, following the trend of Magsat lows.

Such anomalies have not been available for interpretation before the era of satellite geomagnetic surveys. Their interpretation is certainly in its infancy. But the existence of anomaly patterns that may represent ancient or unexpected current geodynamic activity may have profound benefits in terms of our understanding the geologic setting, history, and resources of the Earth.

The continued refinement of satellite magnetics, and no less importantly, the integration of a new generation of satellite gravity data collection into a combined Geopotential Research Mission may allow for the availability of improved satellite gravity and magnetic data with which to conduct crustal and other studies. It may also encourage the refinement of data processing, analytical, and interpretive techniques as researchers improve their abilities in working with global data.

Reference

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DO MAGSAT ANOMALIES CONTAIN A RECORD OF PAST AND PRESENT-DAY MANTLE CONVECTION UNDER SOUTH AMERICA?

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Global anomaly maps from the National Aeronautics and Space Administration's Magnetic Field Satellite (MAGSAT) have been spatially filtered to reduce the prominence of long-wavelength east-west bands and to improve the discrimination of anomalies within structural provinces.

Previous research has suggested a correlation between total-field MAGSAT anomaly lows in equatorial regions with crustal bodies of relatively high average magnetic susceptibility (such as Archaean shields), and of anomaly highs with bodies of low susceptibility (such as deep parts of basins). These correlations reverse at higher latitudes.

The filtered data show a trend of magnetic lows between Buyana and southern Peru. This trend aligns with that of the contact between Africa and North America in a hypothetically reconstructed Pangea. Interpreted as being caused by a regionally higher susceptibility above the Curie point, the anomaly lows might be associated with crustal uplift, mafic intrusion, or higher metamorphic grade. The existence of Mesozoic grabens and other reported features characteristic of extension suggest that the interpreted higher susceptibility may be remnant of convectional upwelling that opened the Atlantic Ocean farther north along this trend, but which failed to form an ocean along this trend in South America.

The Middle America Trench is marked by high MAGSAT anomalies flanked to the east by MAGSAT lows. This anomaly trend continues across South America to the Santos Basin and the Rio Grande Rise (Atlantic Ocean), and fits the association of equatorial MAGSAT highs with trenches and basins, and of MAGSAT lows with uplifts. It suggests that convective downwelling may continue along this trend, causing crustal warping of the South American continental crust in addition to subducton, trenching, and mountain building along the Pacific margin of Central America.

Reference

Hastings, David A., 1984. Do MAGSAT anomalies contain a record of past and present-day mantle convection under South America? Geological Society of America Abstracts with Programs, v. 16, no. 6, September 1984 (in press).

GRM CONFERENCE - PANEL DISCUSSION

Kaula-- The plan of the discussion is for each session Chairman to give his impressions of the main themes of his session, and then for others to give their comments. The first of our chairmen - Don Turcotte - is not here - but Marcia McNutt has agreed to be the reviewer for the Continental Lithosphere. We also agreed that we are not confined to what has been said here, but could interpolate or extrapolate according to our otherwise learned knowledge.

McNutt -- I will attempt to review the work presented at this meeting, as well as other recent studies of which I am aware, in the area of modeling the continental lithosphere using gravity information. Chris Harrison has agreed to summarize those presentations in the Continental Lithosphere session dealing with interpretation of MAGSAT.

There appears to be two ways in which the acquisition of a global gravity field with the coverage, resolution, and accuracy proposed for the GRM mission can further studies involving the continental lithosphere. On one hand, over vast areas of Asia, South America, Africa, parts of Europe, and Greenland, terrestrial data is either non-existent, of poor quality, or politically unavailable. Studies of the density structure and the thermal and mechanical properties of the lithosphere that have been carried out on high-quality gravity data from the United States, Australia, and western Europe could be extended to other continents with GRM. On the other hand, the existence of a homogeneous, accurate data set which crosses coastlines, borders, and geographic barriers would open up a whole new area of investigation into the dynamic response of the continents to loads above and beneath the lithosphere in the 100 to 1000 km wavelength band. Such studies are not now feasible, but in the same way that the SEASAT mission has expanded the scope of problems addressed with gravity data over the oceans, we might anticipate a similar benefit for the continents with GRM.

Several recent studies utilizing gravity data have revealed new information on lithospheric structure and properties. Using high quality data from Australia, Lambeck presented evidence at this meeting of extremely large gravity anomalies in central Australia over tectonic features 300 m.y. old. These observations contradict our models of passive isostatic compensation, pointing to present-day plate deformation and tectonic reactivation by dynamic plate interactions. Karner and Weissel have also been looking at gravity and topography data in southeastern Australia in order to understand the rejuvenation of the Australian highlands. In their model, the present elevation of the mountains is a thermal consequence of rifting and seafloor spreading in the Tasman Sea. Thus data from the Australian margin will help constrain models of rifting and mechanisms of heat transport in the lithosphere.

Just as hot thermal anomalies can have an important effect on tectonics of the overlying lithosphere, cold thermal anomalies also control continental deformation. Sheffels and McNutt have demonstrated using gravity anomalies from the Transverse Ranges of southern California that overall mechanical equilibrium in this region involves a slab of southern California lithosphere which has underthrust the Transverse Ranges in the last 4 m.y. The slab, which has been mapped by seismic tomography, is compensated from above by elastic flexure of the overlying plates. Kahle presented seismic evidence at this meeting for a similar high velocity slab beneath the Swiss Alps. Gravity information can help us understand the relationship between compensation of the mountains, support for the slab, rigidity of the colliding plates, and the dynamic processes which formed the Alpine belt.

In the preliminary interpretation made from the Soviet admittance functions, it appears that the same sort of models now being proposed for other regions, such as the fractured elastic slab model of Karner and Watts (JGR, 1983), also apply to the Soviet Union. The territory of the USSR contains tectonic provinces spanning all geologic ages with classic examples of Hercynian, Kimmerian, and Alpine orogenies. Conclusions based on admittance analysis are at best tentative, and must be reexamined using actual gravity observations. Such studies would greatly enhance our understanding of the thermal and mechanical behavior of the lithosphere during orogeny.

Of course, many of these projects summarized above benefitted from terrestrial data with tighter resolution than nominally what we can expect from GRM. Nevertheless, we can anticipate observing features in the gravity field over scales less than 100 km, though not with the 1 to 2 mgal accuracy level. At the very least, GRM would allow us to extrapolate models developed in detail in areas with good terrestrial data to neighboring regions. For example, we could test whether or not the slab mapped beneath the Swiss Alps is a pervasive element in the entire alpine belt.

Finally, GRM would give us the facility to easily cross frontiers in order to map features in the lower lithosphere and upper mantle. Such studies are now becoming commonplace in the geologically simpler ocean basins. As our under-standing of continental rheology and tectonics improves, it will become easier to strip off the effects of surface complexities in order to view the gravity signature of deeper phenomena. The GRM field will be the key data set for addressing this problem.

McKenzie - Most models of gravity anomalies over continents assume isostasy. What about the dynamic effects?

McNutt -- That is a good point. I think we are entering a new phase of gravity interpretation such that dynamic forces from the mantle can be convincingly included and modeled. In general, gravity information must be supplemented with geologic and seismic data. For example, Royden and Karner have used deep seismic sounding data from the Carpathian foreland to model underthrusting of the Russian plate. The dip of the plate is inconsistent with loading by topography alone. Gravity data from the mountains and the Pannonian hinterland could help constrain the form and location of the deeper loads, possibly related to mantle dynamics. GRM could be a principal contributor in this area.

Kaula -- I think there has been a problem in getting support from geologists for GRM because most geologists regard geology as reconstruction of a past record, while what gravity reflects is present balances of forces. Proportionately, a much greater part of the geophysical effort applies to contemporary processes, in contrast to the geological effort. This difference in attitude is apparent in the 1980 report of the Committee on Earth Sciences of the Spaced Science Board, which said that satellite-to-satellite range-rate was first priority for geophysics, but definitely a second priority for geological purposes. This report was quoted in an overly selective way to support TOPEX before GRM. But I think we all agree that any significant unraveling of the gravity signal of the continents requires use of the geology; the geologists involved need to be particularly concerned about ongoing tectonics.

Comment from Floor -- Geophysicists do not give adequate explanations for a lot of geologic phenomena.

Kaula -- Agreed; what we need are models convincing to the geologists of aulacogens, diapirs, and other strange sounding complexes that geologists invoke to explain the data they see.

Are there any more comments on the Continental Lithosphere? If you have second thoughts you can comment later after Brad Hager speaks on the General Lithosphere -- the distinction of which escapes me a bit.

Tony Watts has agreed to speak about the Oceanic Lithosphere. What has been brought out here and what he knows otherwise.

Watts -- In the session on Oceanic Lithosphere, we saw presented evidence that gravity and geoid measurements, in general, have given us a great deal of information about the structure of the earth in the water covered regions. This information was about both the physical properties of the plates themselves and the forces that may drive, or may get put together to drive, the plates. We saw in a number of papers, and I am sure we would have seen in the ones that were missing, evidence of how satellite altimetry, in particular, has helped geologists and geophysicists with processes and structural problems such as: lithospheric flexture; the trends of fracture zones; the thermal structure of fracture zones; and the tectonic settings of individual bathymetric features, especially the numerous non-hot-spot type of sea mounts. We also saw some evidence from altimetry, in another session by

Barry Parsons, on the planform of convection in the mantle. For a GRM rationale, I think it is fair to say it is very difficult for us to use the examples from the oceans, because of the tremendous success of altimetry beginning with GEOS-3. In addition, to test the results from satellite altimetry -- for example, to examine whether their are seamounts in a particular area in the ocean, or to seek the planform of convection -- scientists are turning to ships, not satellites. This turn occurs mainly because there exists a national facility of very well equipped marine geological and geophysical ships, most of which carry several arrays of very high resolution sensors. I think the best thing that emerged in this session was the suggestion that Dave Sandwell made in his talk: that if we are going to develop the rationale, we should look at how our improved knowledge of the oceans helps us understand the continents. Although this sort of rationale was not discussed in the session, I think it is easy to see that all the oceanic work over the years, in which satellite altimetry has played a major role, has given us a much better idea of what to look for in the continents. And certainly the two top things that may emerge from that list would be (1) the lithospheric flexure problems -- especially in regions of the continents that are acting quite rigidly, thus giving very large gravity or geoid anomalies -- and (2) the general problem of convection in the continental regions. I haven't said anything about magnetic studies discussed in two papers by John LaBrecque and Herb Frey. The satellite magnetometry differs from the gravimetry in that there is not a great deal of correlation with results from marine geophysics, such as the patterns of sea floor spreading anomalies. But we do see a hint in the MAGSAT information that there may be a crustal component, which, from John LaBrecque's talk, could be useful in testing gross models for crustal thickness. From Herb Frey's talk, the MAGSAT data give perhaps some additional information about boundaries between oceans and continents.

Question from Floor -- How has altimetry helped understand the intermediate wavelengths of the gravity field?

Watts -- Well, I think there are a number of studies that have been carried out. The intermediate wavelengths, of course, are of very great importance, as was brought out in several of the papers. The GEOS-3 data set has been used by geophysicists to look at wavelengths in the intermediate wavelength band, and a lot of information has come out from studying correlations of GEOS-3 wavelengths with sea floor topography, for example. So I think there are a number of examples where it has been used and has been a most valuable data set in which to get at the intermediate wavelengths. While ship gravimetry fails because it responds too well to short wavelengths, and the data from satellite tracking in the past has been essentially too long in wavelength, altimetry seems to have served the role at the intermediate wavelengths.

Question from Floor -- How will improvement in the long wavelength part of the gravity field contribute?

McNutt -- Well, I think there are two things to consider. One is how long wavelength errors in geoid height translate into gravity field errors, since gravity is a derivative of that field. Secondly, given the fact that there is a degradation in the altimeter data due to orbit errors, given the improvement of the field by GRM, how much will it change our ability to look at these features and what we can resolve from them. Certainly GRM will do better at intermediate wavelengths. The question is -- is it enough to make a difference and an important difference?

Apel -- If I understand the expected output of GRM correctly, the intermediate wavelengths should be very well derived as regards the geoid, and the associated orbit determination for satellites like TOPEX should be exceedingly good as a result of the GRM field itself. My own view is that when this task is done, the concatenation of the GRM gravity data, with land gravity and with the altimetric geoid (with the oceanographic signals subtracted out) ought to specify surface gravity and gravity at height with exquisite precision. It is hard to imagine right now what more you could want when this task is done.

Kaula -- Anything more on the Oceanic Geoid? We will have a chance to return to this after John Apel speaks. The next listed topic is the General Lithosphere, although I hope Brad Hager follows the example of the two previous speakers and plunges deeper and broader than just the Lithosphere.

Hager -- This General Lithospheric session was split between Magnetics and Gravity, and again, I will pass on the Magnetics to Chris Harrison and comment only on gravity. In terms of lithospheric structure, Don Turcotte presented models based on the mass dipole approach to geoid anomalies which support the point that Dan McKenzie made that the GRM mission will be very useful in looking at various models of mountain building. Turcotte showed us a number of crustal-thickening versus lithospheric-thinning models which can be resolved by looking at gravity. Since a lot of the tectonic action is occurring in fairly inaccessible areas like the Indian-Eurasian Collision, it is important to get good gravity data there. He then plunged into Iceland, where it is clear that mantle dynamics are involved in the dynamic support of Iceland and the generation of the geoid anomaly there. More is involved in the gravity field than just isostasy within the lithosphere.

Dave McAdoo's presentation provided a good approach to interaction of the lithosphere with the underlying fluid mantle. Dave addressed the geoid signature of subducted slabs in the mantle. In this case the density contrasts are fairly well known. This type of situation gives us a good chance to learn something about mantle rheology. He showed that there are basically two ways you can explain very long wavelength anomalies, longer than 4000 kilometers, in the gravity field. It can be done either with a stratified Newtonian viscosity (viscosity as a function of radius only), or viscosity as a function of stress only. I think that Bill Kaula brought up a very good point that at shorter wavelengths one can distinguish between these two models. They have different signatures at short wavelengths. In the particular case of subduction zones, you need to have gravity data spanning the transition from oceans to continents, and it is in an area like this where GRM is ideal.

The final point I would like to make is that these better data will require more complicated and more realistic models, and so we shall learn something about what the earth is doing. Turcotte's presentation of Iceland shows that the data require a more sophisticated model than only lithospheric isostasy. Dave McAdoo's subduction zone problem is another example. Matching the short wavelength gravity field will force us to go to more realistic rheological distributions. Also, in the first session, Kurt Lambeck showed that he had to appeal to anisotropic flexural rigidity to match some of the gravity observations over Australia. Again, this is an indication that it is necessary to move beyond simple spectral approaches and have good spatial coverage of the data to constrain models of tectonic processes.

Kaula - Any Comments? No. Apparently you spoke with the voice of authority.

,The next section on Mantle Convection gave me some feelings of deja vu: firstly, a lot of us still tend to regard mantle convection as all one connected problem; and secondly, we still have essentially spherically symmetric material properties for the various models being presented. It was identified that we still need better information of certain fundamental parameters, most noticeably the viscosity and how it varies with pressure, temperature, and stress, such as in the papers by Rick O'Connell and David Yuen.

But the highlight of the session was "my what a nice difference having some seismology makes." The work by Brad Hager utilizing the inversions by his colleagues at Caltech (Dziewonski and Clayton) of the seismic velocity anomalies in the mantle, very precisely explains the low degree harmonics two, three and four. This result depends on a free parameter which is the ratio of density to the seismic velocity, plus models of subducted slabs and post-glacial rebound. It accounts for almost 90% of the variance up through about the 9th degree. If one indulges in the respectable, if not proper, art of linear extrapolation, the rate-of-progress that has been made in the last year in explaining the gravity field indicates that by the earliest date we can get a GRM, 1991, we will feel that it is way overdue; we shall be overready for it. Let us hope this is one linear extrapolation that prevails and doesn't level off to a new plateau, the way most of them do.

We also identified that there are still several problems remaining. That there are multiple scales of convection is becoming more of a conviction. If, as Dan McKenzie suggested, there are three, we are halfway up to Dick Peltier's six modes of relaxation. But to me, the most persuasive evidence of scale from examination of data was the work by Barry Parsons showing a washboard picture of the Central Pacific and tying it quite persuasively to smaller scale convection in the mantle. I find myself that this is another reminder of the extraordinary variation in properties that we have in the outer zones. The massive screen of the lithosphere keeps us from seeing a lot of variation in the mantle. Other factors leading to multiple scales are the weaker asthenosphere and below that, a barrier of some sort, an inhibitor at 600-700 kilometers. All of these conditions are certainly important in making the picture more complicated and difficult to infer. Something else which was only lightly touched upon, going still deeper in the mantle, is that there may be changes of an order-of-magnitude or more in the viscosity. Hager's best fitting model involved a factor of 30 in the viscosity. There may be other effects, such as a significant decrease in the coefficient of thermal expansion, as we go deeper. The contemporary bland picture of the lower mantle is something which will gradually fade away with time as various factors get sorted out, and our understanding of these effects increase.

Regarding GRM, what does greater resolution give us? We are trying to infer the effects of competing parameters on a set of phenomena which are representable by a spectrum. The wider the spectrum you get, the more likely you are to find some sort of a change in that spectrum which is diagnostic. Brad has already mentioned one: that with finer spectra in certain key areas, such as subduction zones, we might be able to eventually sort out the eternal ambiguity as to whether you need to invoke non-linear viscosity or can explain the observations by multiple layering of Newtonian viscosity. I am still quite sure that we have not yet resolved the question as to what is the proper viscosity, particularly in the upper mantle, for mantle convective purposes. It is not necessarily the viscosity inferred from post-glacial rebound, which involves a time scale differing by a factor of 10^4 and stress levels which differ by a factor of 10 or more. So in our arbitrarily decided differentiation of topics of mantle convection from lithosphere, I think there is a lot that remains to be inferred which would be greatly helped not only by using the shorter wavelength data to strip off the lithospheric and crustal effects, but also to infer alternatives between different hypotheses as to material properties, patterns of convection, etc., in the upper mantle, in conjunction with things like laboratory studies of the material parameters and computer modelings of convection, as computer capabilities increase.

Now we move on to the next topic on the program: the Oceanic Circulation, which will be reviewed by John Apel.

Apel -- In my view, there are three areas where GRM will contribute to physical oceanography. I have to admit that I am always mildly amused to find myself in the company of solid earth geophysicists in this endeavor, but this has been an exceedingly interesting tutorial for me, and I certainly appreciate the chance to hear all of the work that has been described. In any event these three areas in physical oceanography relate to satellite studies using other technologies. Altimetric satellites as we all know need very precise orbits, and Byron Tapley and Jim Marsh both demonstrated the need for these orbits. The improved gravity field from GRM will enable the specification of the gravity field at altitude, as distinct as from the surface, to an outstanding precision. The TOPEX mission will require radial orbit accuracy at the decimeter level. This can be achieved with Doppler or laser tracking if the gravity field is accurately known up to degree and order of approximately 30. GRM is expected to deliver the gravity field to degree and order of 180, more than adequate for future altimetric satellites requiring precise orbit determination.

The second area, of course, is in the specification of the marine geoid, and here, for reasons that I don't altogether understand, nature seems to be working on the side of the physical oceanographers. That is to say, if the marine geoid is an equipotential surface from which ocean surfaces depart due to dynamics, then the longer the oceanic feature, the more precise the geoid needs to be known. Bob Stewart made the point that over basin scales, which the sub-gyre circulation spans, you need very precise geoids indeed. I think that it is very fair to say that over those basin scales, the noise in the GRM geoid ought to be a very few centimeters. I tried to make the point that over shorter scales, on the mesoscale, the oceanic signal was considerably larger, a meter, as shown by data of Marsh and Cheney and others. The horizontal scale over which this meter elevation occurs is of order 100 kilometers. The GRM geoid, again, at shorter wavelengths will have larger noise, but in terms of ocean signal to geoidal noise, the signal to noise ratio is about constant. The additional point I made is that while the half wavelength resolution is specified as approximately 100 kilometers, the inverse wave number is about 35 kilometers. In terms of fluid dynamics, that is the right length to match the edge of mesoscale features such as the Gulf Stream and detached rings and eddies. So in this sense of both horizontal scale and signal to noise ratio, GRM matches the physical oceanographic requirements rather well.

The third area of contribution by GRM involves sea height variability. I must add that there is some confusion, even in my mind, as to what is required for the time varying component of the ocean circulation as compared to what is required for the time independent component. The time variability can, to a considerable degree, be separated by looking at sea height fluctuations from repeat orbits. But you can't do the job for all scales of interest without orbit accuracy of 10 centimeters, and that requires GRM in any event. So TOPEX and GEOSAT, or any other satellite that is to do the altimetric job that is expected of it, will need GRM kind of data, and, in my own view again, it is unfortunate that GRM has been delayed past GEOSAT and TOPEX. Rather I think it should have been flying long since, and those data would be available then when the altimetric satellites fly. That is water over the dam.

Finally, since I have grown a beard and it is gray, I exercise a privilege of graybeards and reflect on history. In the satellite programs that I have been involved with, it has invariably been the case that these precision measurements have yielded more in the final analysis than their proponents ever specified in the beginning. The proponents are wise and don't over-specify to be sure, and I think that would be the case with GRM. I would expect, that -- just as with Transit, the navigation satellites, MAGSAT, LANDSAT, all three GEOS's, and SEASAT -- GRM will provide some serendipitous discoveries which will only be clearly appreciated or even foreseen until well after the fact. That is something that we can look forward to, although it is not necessarily a hard case to make to funding agencies. That is about all - I am happy to answer questions.

Kaula -- Following up on John's last remark: I wish some day NASA would compile a catalog of all the satellite findings, starting with the VanAllen Belts, that were totally unexpected. This should give the best rationale you could have for further projects.

McNutt - Can I make one comment? To some extent, those interpreting the magnetic fields have a slightly easier problem than those interpreting the gravity field, from the standpoint that the insulating mantle means that you have two different sources that have more or less different spectral regimes. Those considering the crustal field can look in a certain wavelength band and those looking at the core field look in another band, $L<13$. It is a slightly easier problem than the gravity field where we don't have this wavelength separation of the two sources. To some extent right now we are at a point where those doing mantle convection have been working with the spherical harmonics, have been explaining the lower harmonics and are moving up the spectrum. Those who interpret gravity anomalies on the continents and in the oceans due to crustal sources, are to the point where they have been explaining the shorter wavelength anomalies and want to move to the longer wavelength anomalies. We are at a point now where we must realize that these are coupled systems, that flow in the mantle affects the lithosphere and lithospheric loads, while subduction and delamination affect flow in the mantle. The two groups are working together from different directions and are at a point now where they should be able to communicate via the same data set. Having one data set that will encompass both regimes would be a great help in further progress in explaining these mid-wavelength anomalies.

Harrison -- I would like to start off in response to Marcia McNutt by pointing out that magnetizations and susceptibilities can vary by orders of magnitude for rocks which look almost exactly the same, so we have this big problem which was, I think, pointed out by Wasilewski, that our knowledge of the magnetic properties of rocks is really still quite limited and this is one of the things that we really have to work on in order to find out what are the magnetic properties of the lower continental crust or the oceanic crust. When people look at rocks coming from the lower continental crust, it is often difficult to know whether the magnetic properties they measure in them are those which were in existence when they were in the lower continental crust. It is quite possible that when the rocks were uplifted their magnetic properties were changed. This is seen often in oceanic rocks, called ophiolites, which are sections of the oceanic crust which are placed on the continents and very frequently there you can show that the magnetic properties which were measured on these things are probably not what they were like when they were in the ocean basin. So I think that is one point I would like to make. I would like to reiterate what Bob Langel said, which is that we need more quantitative models. We need to know what the susceptibility contrasts or the magnetization contrasts are to explain the magnetic anomalies we are seeing. So it is gratifying to see people working on spherical harmonics up to sufficiently high degrees that they are probably capturing much of the crustal field which can be seen at satellite altitudes. Now whether this can be done with GRM, where you would have to go up to degrees of 200 or more, I don't know, but that is a gratifying thing to see. I was also gratified to see several people doing quantitative models where they invert the magnetic fields to get magnetizations, for instance, the work done by John LaBrecque in the North Atlantic. I think it is quite obvious from the lower altitude of GRM that we shall be seeing some details of the magnetization produced during the Tertiary, when the field was reversing fairly rapidly. I think there will be signals coming from those portions of the oceanic crust where the spreading rates have been fairly high. I think we will be seeing several nanoteslas of signal over those areas which will be very useful for tying down what the magnetic crust is like. Bob Langel did mention this controversy as to whether vector field data were useful in GRM, and I think we have solved that problem in private discussions. I think that the problem is that if you have, for instance, a vertical source, and you measure it using a horizontal field, the field directly over the source is going to be zero. To get a horizontal signal from that source you have to move away, and then your $1/r^3$ factor means that your anomalies tend to be rather small. Certainly if you have vector data, you will get a larger signal to noise ratio in those situations. I would like to see more studies done on correlation of magnetization with things like heat flow. The paper that Mike Mayhew wrote a couple of years ago, correlating magnetization with the depth of the Curie isotherm, is the sort of thing that we should be doing. Of course, it would be much easier with GRM because we will be looking at shorter wavelength features which should hopefully match the heat flow data much better. I think it would also be possible to do this with data on the depth to the Moho. When we invert magnetic fields, what we are getting is essentially an integrated vertical indication of what the magnetization is. This can either be caused by variations of susceptibility or intensity or just a variation in the thickness of the magnetized layer. I would like to see studies done where the magnetization is correlated with the thickness to the Moho, for instance, where one could use gravity anomalies to get those data. There are still some problems with separation of the core and crustal field. Bob Langel pointed out that in one case it is impossible to look at the crustal field in the very low degrees of harmonics because they are completely swamped by the core field, and there is, I think, no way of making this separation, other than what the German group did, which is to model, using reasonable susceptibility values, the various types of provinces over the surface of the Earth. Of course, when you do that, you do see a distinct difference between continental and oceanic magnetic fields. I was not present when the three papers on the main field were given, and I have asked Bob to make some comments about the Main Field and GRM. This aspect will not be so important if the Magnetic Field Explorer gets under way, but in case that it does not, we are still very concerned about getting good Main Field measurements in order to tie down various aspects of the secular variation.

Langel -- I don't know how many of you are aware of it, but there is a revolution taking place in Main Field geophysics. For the past few years those doing main field models have been talking to the people who are trying to interpret the models, and really trying to begin to work together. We seem to be getting to the place, with some of the more recent models where we are isolating some features of the magnetic field that are really present at the core-mantle boundary. While there may be some disagreements as to exactly how much we know, it is fairly clear that our knowledge of the field at the core-mantle boundary is increased by an enormous amount with some of the new modeling techniques. This is largely due to the smooth models that were begun by Shure and her colleagues, and followed up in a different way by Dave Gubbins at Cambridge. I think these developments are rather exciting. I expect that in the future, particularly if we can get a better handle on secular variation, we will be able to extend the types of analysis that can be done, and learning considerably more about the fluid velocities at the core surface better than we know now. Hopefully, we won't need GRM to do that. We also hope that we get the Magnetic Field Explorer (MFE) mission, but if we don't and if GRM is up first, then it will be a real valuable contribution to the determination of the main field. The studies that Coerte Van Voorhies and others are doing are also exciting. They are trying to isolate possible fluid flows at the core-mantle boundary and provide us with hypotheses that can be tested with the models and data. I think that the fact that we are really beginning to communicate with each other at this point is going to make the advances over the few years come even more rapidly and that is encouraging to me.

Harrison - Any Questions? No.

One other thing that I would like to point out to Marcia McNutt is that gravity is vertical gravity and we have to deal with magnetic fields which are measured in all sorts of very peculiar directions.

McNutt - yes, but we have deflections of the vertical too.

Apel - It is clearly a gray situation.

Harrison - We are intending to write a report about this meeting which will be published in EOS and we may be asking various of you to make some small contribution to this report. We have been taking extensive notes. We also have been recording these proceedings and these will be the basis for our report, but we may be asking some of you to give us some additional information.

Kaula - In fact, if you don't trust us to get it straight, you can volunteer some pieces.

Harrison - Does anybody have any final comments about this or any questions about GRM or MAGSAT or MFE?

Harrison - Thank you all for coming. I have enjoyed the conference. I don't think we had enough controversy, but maybe if we had been in a smaller room, we would have been fighting more.

APPENDIX A
GEOPOTENTIAL RESEARCH MISSION SCIENCE CONFERENCE

SCHEDULE

Monday, October 29, 1984

I. INTRODUCTION (Chairman: W. Kaula)

8:00 a.m.	Registration	
9:00	Convening	W. Kaula C. Harrison
9:15	Welcome	D. Smith
9:30	Keynote	B. Edelson
9:50	Status and Plans	T. Fischetti E. Flinn T. Keating
10:30	Coffee Break	

II. CONTINENTAL LITHOSPHERE (Chairman: D. Turcotte)

10:40	Impact of GRM: New Evidence from the Soviet Union	M. McNutt
11:00	Dynamics and Structure of the Continents (Especially Alpine Fold Belts)	H.G. Kahle
11:20	Why Do We Need Detailed Gravity Over Continents: Some Australian Examples	K. Lambeck
11:40	A Major Crustal Feature in the Southeastern United States Inferred from the Magsat Equivalent Source Anomaly Field	M. Ruder
12:00	Lunch	
1:30 p.m.	Geophysical Interpretation of the Magnetic Anomalies of the Earth Derived from Magsat Data	J. Arkani-Hamed
1:50	Satellite Magnetic Modeling of North African Hot Spots	R. Phillips
2:10	Magnetic Structure of the Crust	P. Wasilewski

Monday, October 29, 1984 (cont'd)

III. OCEANIC LITHOSPHERE (Chairman: A. Watts)

2:30	Gravity, Geoid and the Oceanic Lithosphere	A. Watts
2:50	Thermal Cooling of the Oceanic Lithosphere from Geoid Height Data	A. Cazenave
3:10	Studies of the Maraine Crustal Magnetization at Intermediate Wavelengths	J. LaBrecque
3:30	Coffee Break	
3:45	Lithospheric Structure in the Pacific Geoid	B. Marsh
4:05	The Gravity Field of Topography Buried by Sediments	D. Sandwell
4:25	GRM Crustal Magnetic Anomalies: Separating The Lord Howe Rise and Norfolk Ridge Submarine Structures	H. Frey
4:45	Sea Floor Swell	P. Olsen
5:05	Adjourn	

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5:30-7:30 **Reception (Founders Room)**

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Tuesday, October 30, 1984

IV. GENERAL LITHOSPHERE (Chairman: B. Hager)

8:30 a.m.	Properties of the Lithosphere and Asthenosphere Deduced from Geoid Observations	D. Turcotte
8:50	Subduction Dynamics: Constraints from Gravity Field Observations	D. McAdoo
9:10	Continental and Oceanic Magnetic Anomalies: Enhancement through GRM	R. von Frese
9:30	The Resolution of a Magnetic Anomaly Map Expected from GRM Data	D. Strangway
9:50	Coffee Break	

Tuesday, October 30, 1984 (cont'd)

V. MANTLE CONVECTION (Chairman: W. Kaula)

10:20	The Importance of GRM Gravity Observations in Continental Regions	D. McKenzie
10:45	The Sources of the Earth's Long Wavelength Geoid Anomalies: Implications for Mantle Core Dynamics	B. Hager
11:10	Interpretation of the Geoid	K. Runcorn
11:35	Mantle Convection and the Large Scale Structures of the Earth's Gravitational Field	W. Peltier
12:00	Lunch	
1:30 p.m.	Constraints on the Rheology Structure of the Mantle	R. O'Connell
1:55	The Role of a Pressure-Dependent Rheology in the Dynamics of Mantle Circulation	D. Yuen
2:20	Small Scale Convection Beneath the Transverse Ranges in California: Implications for Interpretation of Gravity Anomalies	B. Hager
2:45	Evidence from Satellite Altimetry for Small Scale Convection in the Mantle	B. Parsons
3:10	Mantle Viscosity, J_2 and the Nontidal Acceleration Earth Rotation	W. Peltier
3:35	Coffee Break	
3:45	Modeling Crustal and Upper Mantle Structures for Gravity and Magnetic Fields	J. DeNoyer

VI. OCEAN CIRCULATION (Chairman: J. Apel)

4:10	On the Geographical Correlation of Orbit Error	B. Tapley
4:30	Global mean Sea Surface Computation Based Upon a Combination of SEASAT and GEOS-3 Satellite Altimeter Data	J. Marsh
4:50	Contributions of GRM to the Ocean Topography Experiment (TOPEX)	R. Stewart
5:10	Adjourn	

Wednesday, October 31, 1984

VII. MAGNETICS (Chairman: C. Harrison)

9:00 a.m.	Separation of Core and Crustal Magnetic Field Sources	L. Shure
9:20	The Magnetic Field at the Core Mantle Boundary	J. Bloxham
9:40	Some Anticipated Contributions to Core Fluid Dynamics from the GRM	C. Voorhies
10:00	Coffee Break	
10:25	Rationale for a GRAVSAT-MAGSAT Mission. A Perspective on the Problem of External/ Internal Transient Field Effects	J. Hermance
10:45	Recent Magsat Results	J. Cain
11:05	Modeling Currents at Satellite Altitudes	G. Backus
11:25	Expected Contributions of GRM to Studies of Liquid Core Fluid Dynamics	E. Benton
11:45	The Source of the Intermediate Wavelength Component of the Earth's Magnetic Field	C. Harrison
12:05	Lunch	
1:30 p.m.	Does the Geoid Drift West?	G. Backus
1:50	GRM as a Follow-On to Magsat	R. Langel
2:10	Coffee Break	
2:45	Panel Discussion: Highlights and New Considerations	J. Apel B. Hagar C. Harrison W. Kaula M. McNutt A. Watts
4:15	Adjourn	

APPENDIX B

ATTENDEES

Name	Organization
1. Achache, Jose	Institut de Physique du Globe
2. Alexander, Shelton S.	Pennsylvania State University
3. Anderson, Allen J.	University of Uppsala
4. Apel, John R.	APL/JHU
5. Arkani-Hamed, Jafar	University of Toronto
6. Arvidson, Raymond E.	Washington University
7. Babcock, Alice	Naval Observatory
8. Backus, George E.	Univ of California at San Diego
9. Barresi, Giangrande	Ecosystems International
10. Benton, Edward R.	University of Colorado
11. Berg, Joseph	National Research Council
12. Black, Harold	APL/JHU
13. Bloxham, Jeremy	University of Cambridge
14. Briggs, Geoffrey	NASA Hdqts
15. Brown, Tom C.	--
16. Brown, Carolyn	Southern Methodist University
17. Burke, Kevin C.	Lunar and Planetary Institute
18. Cain, Joseph C.	U.S.G.S., Boulder
19. Cande, Steven C.	Lamont-Doherty
20. Carpenter, Lloyd	NASA/GSFC
21. Chase, Clement	University of Arizona
22. Chovitz, Bernard	NOAA/NGS
23. Christodoulidis, Demos	NASA/GSFC
24. Coleman, Paul	Univ. of California at Los Angeles
25. Colombo, Oscar	EG&G WASC
26. Connerney, John	NASA/GSFC
27. Dachel, Peter	Bendix

ATTENDEES (cont.)

28. DeNoyer, John	U.S.G.S./Reston
29. Decker, Winfield	Bendix
30. Decker, Louis	DMA Aerospace
31. Douglas, Bruce C.	NOAA/NGS
32. Dunn, Peter	EG&G WASC
33. Dziewonski, Adam	Harvard University
34. Edelson, Burton	NASA Hdqts
35. Estes, Ronald	BTS
36. Felsher, Murray	Associated Technical Consultants
37. Finley, Charles	NASA Hdqts
38. Fischetti, Tom	NASA Hdqts
39. Flinn, Edward	NASA Hdqts
40. Frawley, James J.	HBG
41. Frey, Herbert	NASA/GSFC
42. Fundak, Terry J	Air Force Geophysics Lab.
43. Gaposchkin, E. Michael	Lincoln Laboratories
44. Gevirtz, Bruce	Bendix
45. Gettings, Mark	U.S.G.S.
46. Goad, Clyde	NOAA
47. Gross, M. Grant	National Science Foundation
48. Gude, Joe	SCINTREX
49. Hager, Bradford	CalTech
50. Hanna, William	U.S.G.S.
51. Harrison, Christopher	University of Miami
52. Hayes, James F.	National Science Foundation
53. Hermance, John F.	Brown University
54. Hertzler, Jim	WHOI
55. Hinojosa, Juan H.	Johns Hopkins University
56. Hinojosa, Patricia M.	Johns Hopkins University
57. Hinze, William J.	Purdue University
58. Johnson, Rick	Bendix

ATTENDEES (cont.)

59.	Kahle, Hans-Gert	Institut fur Geodasie und Photogrammetrie, Zurich
60.	Kahn, Werner	NASA/GSFC
61.	Kant, Seymor	NASA/GSFC
62.	Kaula, William	NOAA/NGS
63.	Keating, Tom	NASA/GSFC
64.	Kerr, Richard	Science Magazine
65.	Kingham, Kerry	Naval Observatory
66.	Kisabeth, Jerry	CONOCO, Inc.
67.	Klosko, Steve	EG&G WASC
68.	LaBrecque, John L.	Lamont-Doherty
69.	Lambeck, Kurt	Australian National University
70.	Langel, Robert	NASA/GSFC
71.	Laubscher, Roy E.	Geodynamics Corp.
72.	Lazarewicz, Andy	Air Force Geophysics Lab
73.	LeFebvre, Michel	CNES, France
74.	Lerch, Frank	NASA/GSFC
75.	Lorenzini, Enrico	Smithsonian Astrophysical Obs.
76.	Marsh, Bruce D.	APL/JHU
77.	Marsh, James G.	NASA/GSFC
78.	Martin, Chreston F.	EG&G WASC
79.	Mayhew, Michael A.	National Science Foundation
80.	McAdoo, David	National Geodetic Survey
81.	McCarthy, Dennis	Naval Observatory
82.	McKenzie, Dan P.	Bullard Labs/Univ of Cambridge
83.	McNutt, Marcia	MIT
84.	Mead, Gilbert	NASA/GSFC
85.	Meyers, Herbert	NOAA/EDIS
86.	Mueller, Ivan	Ohio State University
87.	Nam, In Seung	Johns Hopkins University
88.	O'Connell, Richard	Harvard University
89.	Olson, Peter L.	APL/JHU

ATTENDEES (cont.)

90. Ousley, Gilbert	NASA/GSFC
91. Parsons, Barry E.	Massachusetts Institute of Tech.
92. Peltier, W.R.	University of Toronto
93. Phillips, Roger	Southern Methodist University
94. Phillips, Jeffrey D.	U.S.G.S./Reston
95. Pisacane, Vincent	APL/JHU
96. Pyle, Thomas	NOAA
97. Rapp, Richard	Ohio State University
98. Raymond, Carol	Lamont-Doherty
99. Robbins, John W.	Ohio State University
100. Ruder, Michal E.	Pennsylvania State University
101. Runcorn, Keith	University of Newcastle
102. Sandwell, David	National Geodetic Survey
103. Schnetzler, Charles	NASA/GSFC
104. Schupler, Bruce	Bendix
105. Schutz, Robert	University of Texas
106. Seigel, Harry	SCINTREX Limited
107. Shapiro, Irwin	Smithsonian Astrophysical Obs.
108. Shure, Loren	Woods Hole Oceanographic Inst.
109. Singer, Harvey A.	Johns Hopkins University
110. Siry, J.	NASA/GSFC
111. Smith, David E.	NASA/GSFC
112. Solar, Tomas	NOAA/NGS
113. Sonnabend, David	Jet Propulsion Laboratory
114. Stewart, Robert	Jet Propulsion Laboratory
115. Strangway, David	University of Toronto
116. Talwani, Manik	Gulf Research Development Co.
117. Tapley, Byron	University of Texas
118. Taylor, Pat	NASA/GSFC
119. Thomas, Herman H.	NASA/GSFC
120. Tilford, S.G.	NASA Headquarters

ATTENDEES (cont.)

121.	Torrence, Mark H.	EG&G WASC
122.	Tscherning, C.C.	Danish Geodetic Institute
123.	Tsurutani, Bruce	Jet Propulsion Laboratory
124.	Turcotte, Donald L.	Cornell University
125.	von Frese, Ralph	Purdue University
126.	Voorhies, Coerte V.	NASA/GSFC
127.	Wagner, Carl A.	NOAA/NGS
128.	Walter, Lou	NASA Hdqts
129.	Wasilewski, Peter	NASA/GSFC
130.	Watts, Anthony	Lamont-Doherty
131.	Wells, William T.	EG&G WASC
132.	Whaler, Kathryn A.	Bullard Labs/Univ of Cambridge
133.	Williams, Owen W.	Retired
134.	Williamson, Ronald G.	EG&G WASC
135.	Wunck, Thomas	Jet Propulsion Laboratory
136.	Yuen, David A.	University of Toronto
137.	Zlotnicki, Victor	NASA/GSFC

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16. Abstract

The Geopotential Research Mission (GRM) Science Conference was held October 29-31, 1984, at the University of Maryland, under the sponsorship of NASA, NOAA, DMA, USGS, NSF, and NAS. The title of the Conference is derived from the GRM, a satellite system proposed to determine variations in the gravitational and magnetic fields to a resolution of about 100 kilometers.

The purpose of the Conference was to review knowledge and interpretations of the potential fields on scales of 100 kilometers and greater, and thus to clarify the needs for better data in this range of wavelengths. In addition, the potential contribution of these data to the determination, by satellite altimetry, of a more accurate geoidal reference was discussed.

The conference was sponsored by the Geopotential Research Mission Science Steering Group/NASA Office of Space Science and Applications, the National Geodetic Survey, the Defense Mapping Agency, the United States Geological Survey, the National Science Foundation, and the Committee on Geodesy of the National Academy of Sciences.

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